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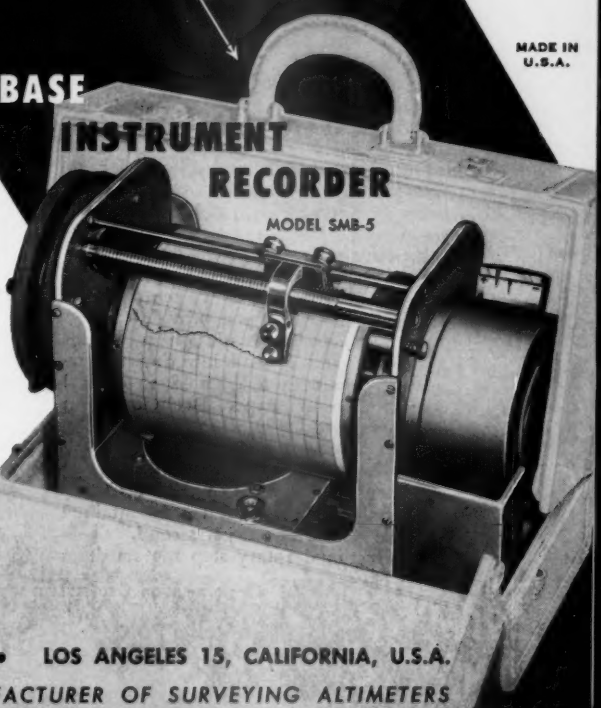

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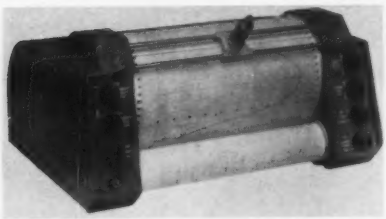

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The new recorder measures 12 inches high, 18 inches wide and 14 inches deep and weighs only 40 pounds. Power requirements are 100 to 130 volts, single phase, 60 cycle at 125 watts.

For additional information about the CCP Model 560-R Digital Incremental Recorder contact: **W. L. Moore, Director of Sales, California Computer Products, Inc., 8714 Cleta Street, Downey, California.**

*(Continued on page 32)*

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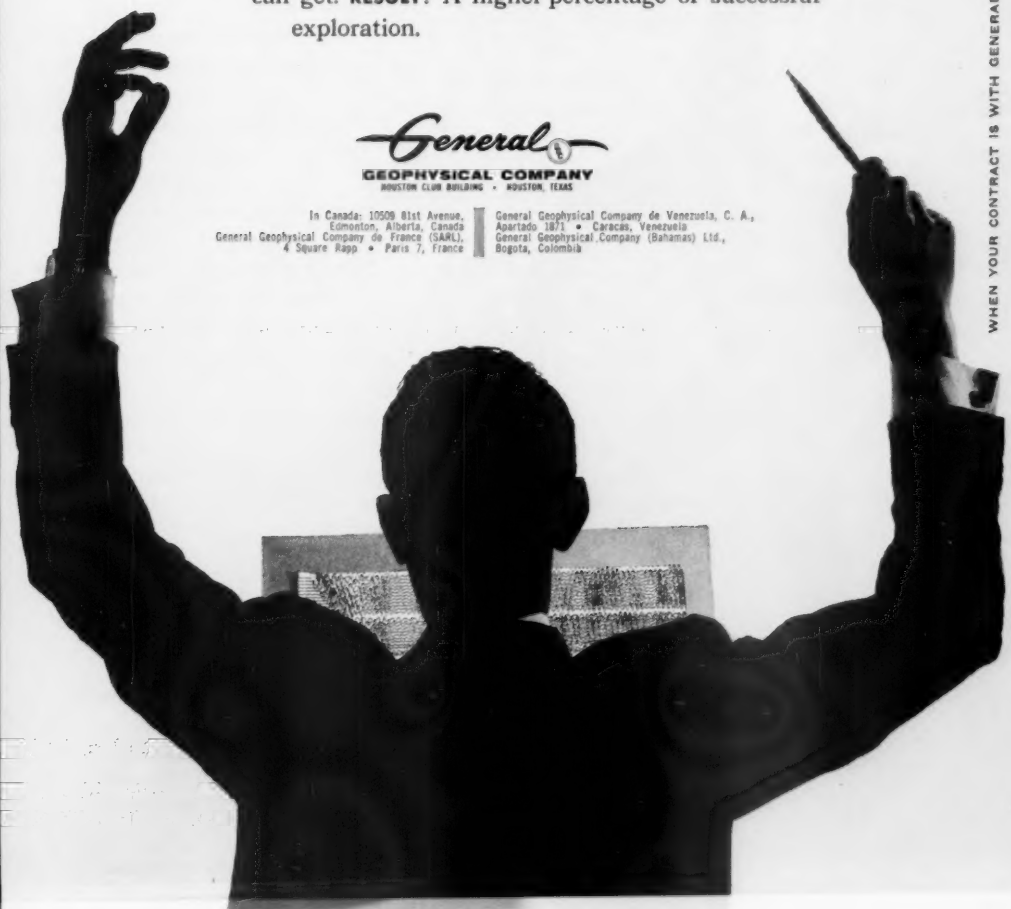

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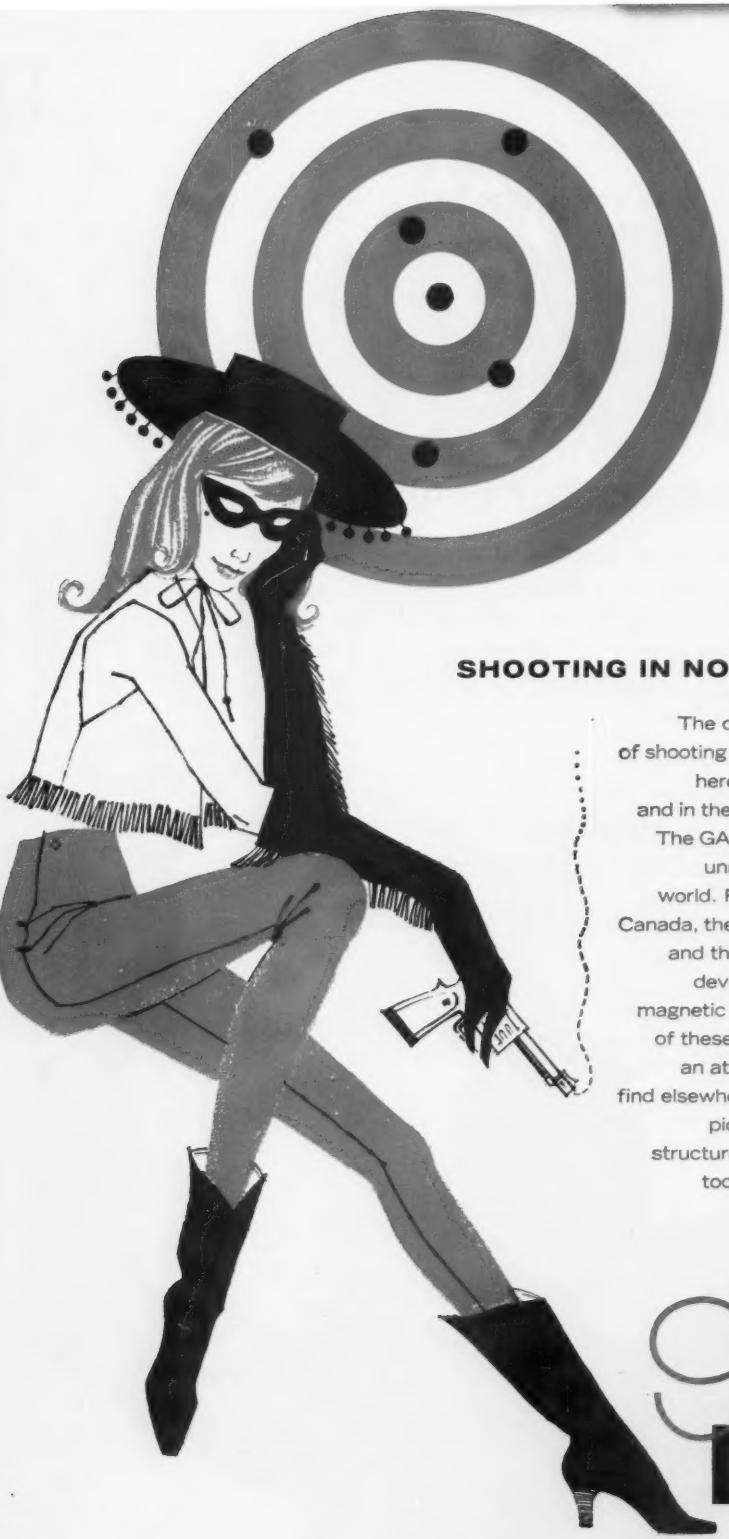

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VOLUME XXV OCTOBER, 1960 NUMBER 5

GEOPHYSICS

# TWO-DIMENSIONAL SEISMIC MODELS WITH CONTINUOUSLY VARIABLE VELOCITY DEPTH AND DENSITY FUNCTIONS*

JOHN H. HEALY† AND FRANK PRESS†

ABSTRACT

A method for fabricating two-dimensional ultrasonic seismic models with variable velocity and density is described. The method is justified theoretically. It is tested by comparing the experimental and theoretical dispersion of Rayleigh waves in a model of a two-layered earth crust.

## INTRODUCTION

Many problems of interest to the seismologist are impossible to solve with available mathematical techniques. Where exact solutions are not available, seismic models can facilitate the development of approximate solutions that are almost as useful as the exact solution, and the seismic model provides the additional advantage of a clear illustration of the results with the model seismograms. Thus, seismic model studies can play a very important role in the study of wave propagation problems.

The assembly of the electronic part of a seismic model system has become a simple task as a result of advances in design and the ready availability of the components. However, practical difficulties involved in the fabrication of the seismic model itself seriously limit the scope of problems that can be studied.

One large class of problems that is important both in exploration seismology and in earthquake seismology is concerned with media that have a continuously variable velocity depth function. This paper describes a method of modeling a medium with variable velocity depth and density functions and illustrates the technique by a study of a problem in Rayleigh wave dispersion. Two dimensional model techniques, as described by Oliver, Press and Ewing (1954), are the basis of this method which makes use of the fact that waves propagating in thin sheets obey the two-dimensional wave equation. A variable velocity is obtained by the

* Contribution No. 969, Division of Geological Sciences, California Institute of Technology. Manuscript received by the Editor January 25, 1960.

† Seismological Laboratory, California Institute of Technology, Pasadena, California.

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use of a laminated sheet in which the relative proportions of the laminae are varied so as to change the average elastic constants (hence the average velocities) of the sheet. The density can be modeled by varying the total thickness of the sheet.

This technique of modeling was suggested originally by Jack Oliver and the method of fabrication used was suggested by H. O. Walker.

## EQUIPMENT

The model set up was essentially the same as described in earlier papers (Oliver, Press and Ewing, 1954). One-eighth inch by one-quarter inch solid cylinders of barium titanate were used as sources and barium titanate bimorph transducers were used as receivers. The bimorph transducers were clamped between rubber sheets to provide sufficient damping to prevent ringing. This simple device proved to be very effective in eliminating the ringing problem.

## MODEL CONSTRUCTION

The models were fabricated from aluminum sheets and an epoxy resin plastic that was poured onto the aluminum and allowed to solidify. The aluminum used was 24ST in .020 inch sheets, and the plastic used was Shell Epon No. 828 with diethylenetrianamene hardener.

The aluminum sheets were cut in circles 24 inch in diameter and mounted to a 26-inch face plate with parafin wax.

A horizontal milling machine available in our shops was converted to a stub lathe so that a contour could be cut in the surface of the aluminum sheet. After the desired contour was cut in the aluminum, the face plate was removed from the lathe and a layer of plastic was poured over the aluminum and allowed to harden.

A final contour was cut in the surface of the plastic so as to provide control of two parameters, the total thickness of the model, and the ratio of plastic to aluminum. Figure 1 shows a portion of the model with source and receiver.

This process, while simple in concept, is a difficult machine shop problem. The tolerances desired exceed the capabilities of the standard machine tools and extreme care is required to obtain a satisfactory model. A great deal of credit is due our experimental machinest, Mr. Carl Holmstrom, for the successful construction of these models.

## THEORY OF TWO-DIMENSIONAL LAMINATED PLATE MODELS

If the the three-dimensional equations of motion and boundary conditions are solved to yield the period equation for a laminated plate with two sheets, it can be shown that for wave lengths, long compared to plate thickness, the phase velocity reduces to a constant value, reflecting the average elastic parameters of the plate.

Another approach is to proceed from the assumption of plane strain and derive

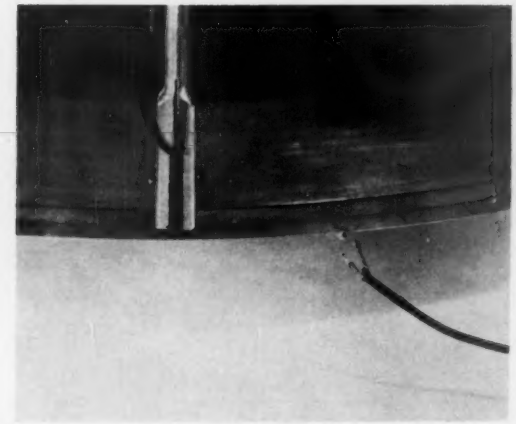


FIG. 1. Layered plate model with a damped bimorph receiver and cylindrical source.

the wave equation for a laminated plate. Consider a plane wave propagating in a layered plate in the $X$ direction so that the particle motion is perpendicular to the surface of the plate. Figure 2 shows the cross section of the plate with the differential element which we will consider. With the following definitions,

$u$ = particle motion in $X$ direction
$T_i$ = thickness of $i$th lamination
$\bar{\rho}$ = density of laminated plate (mass per unit area)
$\beta$ = shear velocity in laminated plate
$C_p$ = plate longitudinal velocity in the laminated plate
$\alpha_i$ = compressional velocity of $i$th lamination
$\beta_i$ = shear velocity of $i$th lamination
$E_i$ = Young's modulus of $i$th lamination
$\sigma_i$ = Poisson's ratio of $i$th lamination
$\rho_i$ = density (mass per unit volume) of $i$th lamination
$C_{pi}$ = plate longitudinal velocity in a homogeneous plate of the composition of the $i$th lamination

the equation of motion in the $X$ direction is,

$$\frac{\partial}{\partial X}\left[\frac{\partial U}{\partial X}\left(\frac{E_1}{1-\sigma_1^2}T_1+\frac{E_2}{1-\sigma_2^2}T_2\right)\right]=(\rho_1 T_1+\rho_2 T_2)\frac{\partial^2 U}{\partial t^2}\cdot \qquad (1)$$

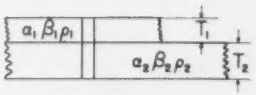



FIG. 2. Cross section layered plate.

This reduces to a wave equation,

$$\frac{\partial^2 U}{\partial X^2} = \frac{\rho_1 T_1 + \rho_2 T_2}{\dfrac{E_1}{1-\sigma_1{}^2} T_1 + \dfrac{E_2}{1-\sigma_2{}^2} T_2} \frac{\partial^2 U}{\partial l^2} . \tag{2}$$

Thus, the plate longitudinal velocity is given by,

$$C_p{}^2 = \frac{\dfrac{E_1}{1-\sigma_1{}^2} T_1 + \dfrac{E_2}{1-\sigma_2{}^2} T_2}{\rho_1 T_1 + \rho_2 T_2} = \frac{\rho_1 C_{p1}{}^2 T_1 + \rho_2 C_{p2}{}^2 T_2}{\rho_1 T_1 + \rho_2 T_2} . \tag{3}$$

Similarly for shear waves one finds,

$$\beta^2 = \frac{\rho_1 \beta_1{}^2 T_1 + \rho_2 \beta_2{}^2 T_2}{\rho_1 T_1 + \rho_2 T_2} . \tag{4}$$

From comparison with the homogeneous plate it is evident that $\bar{\rho} = \rho_1 T_1 + \rho_2 T_2$ replaces the density factor and $\rho_1 \rho_{p1}{}^2 T_1 + \rho_2 \rho_{p2}{}^2 T_2$ or $\rho_1 \beta_1{}^2 T_1 + \rho_2 \sigma_2{}^2 T_2$ replaces the elastic factor.

We have verified equation (3) by solving the exact three-dimensional equations of motion for an infinite laminated plate subject to the exact boundary condition at the free surfaces and the interface. Equation (3) is a limiting form of the solution for phase velocity which emerges from the long wave length condition $\lambda >> T_i$. This result has also been experimentally verified as will be seen in the next section.

It is more difficult to establish the use of equations (3) and (4) and to specify exact boundary conditions when the thicknesses of the lamina are varied to model the velocity and density parameters. One might justify the use of these equations by arguing intuitively from the results of Oliver et al. (1954) for homogeneous plates. We prefer to justify these equations experimentally by study of Rayleigh wave dispersion in a model of a double layered crust overlying a mantle.

Note that the mass per unit area will be the density that must be considered when we vary the thickness of the lamina to model the velocity and density parameters. By suitable choice of $T_1$ and $T_2$ one can model density and one of the elastic constants provided it falls between the corresponding values of the model materials chosen.

## EXPERIMENTAL VERFICATION OF THE THEORY

An experimental verification of the results derived was obtained with a series of layered plates constructed, as described above, of a layer of plastic over aluminum. The total thickness of the plate was $\frac{1}{8}$ inch and the ratio of plastic

to aluminum was varied in 11 steps from all aluminum to all plastic. Velocities of compressional and shear waves in these plates were measured and the results are shown in Figure 3. Good agreement was found for the shear waves, but a marked variation from the theoretical values was shown by the compressional waves.

The cause of this discrepancy was thought to be a violation of the assumption that the wave length of the waves was sufficiently long as compared to the plate thickness. A second series of plates was constructed whose total thickness was only $\frac{1}{16}$ inch and good agreement was found with the theoretical values.

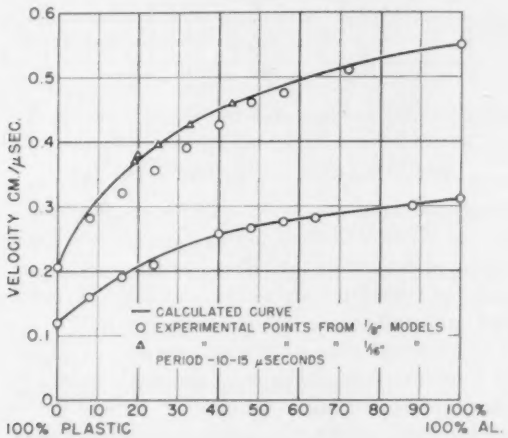



FIG. 3. Compressional and shear wave velocity in plastic and aluminum laminated plates.

As further check on the effect of lamina thickness, the exact phase velocity curve for a two-layer plate with a plastic to aluminum ratio of .040/.085 was computed. The exact period equation was formulated according to Haskell's matrix method (1953) and solved numerically on the Seismological Laboratory's electronic computer, the Bendix G15D. The results are shown in Figure 4. These curves verify that for the periods used, 10–15 micro/sec, there is marked dependence of phase velocity on period in a $\frac{1}{8}$ inch plate. It is interesting to note that the dispersion is more severe for the laminated plate than for the homogeneous plate. We believe this is a result of coupling between the symmetric and antisymmetric waves in the laminated plate. The dispersion in the $\frac{1}{16}$ inch plate is negligible for these periods.

It was concluded that with the materials and frequencies used in our experiment, total plate thickness should be less than $\frac{1}{16}$ inch. In the particular experiment described below, all models were less than $\frac{1}{32}$ inch in thickness.

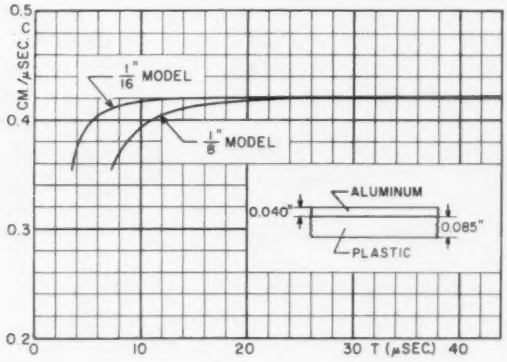



FIG. 4. Phase velocity for a two layer plate .040 inch aluminum and .085 inch plastic.

## PHASE VELOCITY IN A TWO-LAYER CRUST

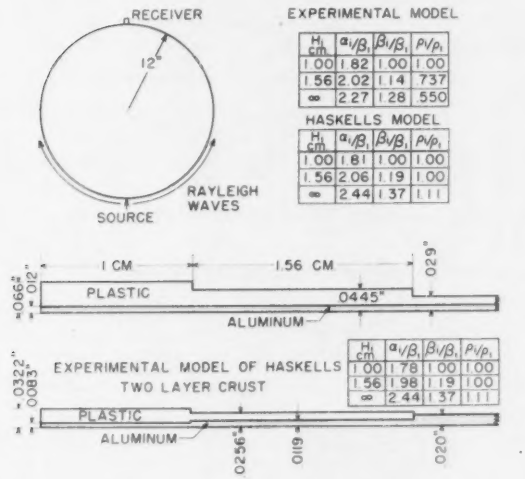
As a preliminary to use of this method in the study of wave propagation in the earth's crust, an attempt was made to reproduce the Rayleigh wave phase velocity in a two-layer crust. Since dispersed surface waves may be regarded as multiply reflected and refracted body waves, a powerful test of a model is a comparison of experimental and theoretical dispersion curves. For this comparison we have selected a two-layered crust overlying a mantle, as computed by Haskell. The first model constructed modelled only the shear wave velocity, neglecting the density and compressional wave velocity.

As the Rayleigh wave velocity is predominately controlled by the rigidity of the medium, one would expect that variations in density and compressional velocity would have only secondary effects on the Rayleigh wave velocity.

The model was a disk 24 inch in diameter with thickness as shown in the top cross section of Figure 5. Both phase and group velocity were measured on this model and the results are shown in Figure 6. The phase velocity falls below the expected values, which was anticipated since we failed to model density.

In the second attempt, we had improved our technique so that we were able to cut a contour in the aluminum sheet and in the plastic, and were able to model both the density and the shear velocity. The lower cross section of Figure 5 shows the thicknesses used in this model.

For the second model, the phase velocity was measured in three ways. One method was to excite the disk model with a continuous sine wave source so as to set up a standing wave on the edge of the disk composed primarily of the Rayleigh wave trains traveling in opposite directions around the disk. This is analogous to exciting a free mode of the earth. The phase velocity could be determined by counting the nodes around the disk. This method was most effective with the longer wave lengths (Figure 7). In the second method the Rayleigh wave




| $H_1$ cm | $\alpha_1/\beta_1$ | $\beta_1/\beta_1$ | $\rho_1/\rho_1$ |
|---|---|---|---|
| 1.00 | 1.82 | 1.00 | 1.00 |
| 1.56 | 2.02 | 1.14 | .737 |
| ∞ | 2.27 | 1.28 | .550 |

| $H_1$ cm | $\alpha_1/\beta_1$ | $\beta_1/\beta_1$ | $\rho_1/\rho_1$ |
|---|---|---|---|
| 1.00 | 1.81 | 1.00 | 1.00 |
| 1.56 | 2.06 | 1.19 | 1.00 |
| ∞ | 2.44 | 1.37 | 1.11 |

| $H_1$ cm | $\alpha_1/\beta_1$ | $\beta_1/\beta_1$ | $\rho_1/\rho_1$ |
|---|---|---|---|
| 1.00 | 1.78 | 1.00 | 1.00 |
| 1.56 | 1.98 | 1.19 | 1.00 |
| ∞ | 2.44 | 1.37 | 1.11 |

FIG. 5. Cross-section of two models with tabulated values of constants.

train traveling in one direction from the source was damped so that the wave train traveling in the other direction propagated without interference, and the phase velocity could be determined by following a particular peak or trough around the disk (Figure 8).

The results of these two methods are shown in Figure 9. Good agreement exists

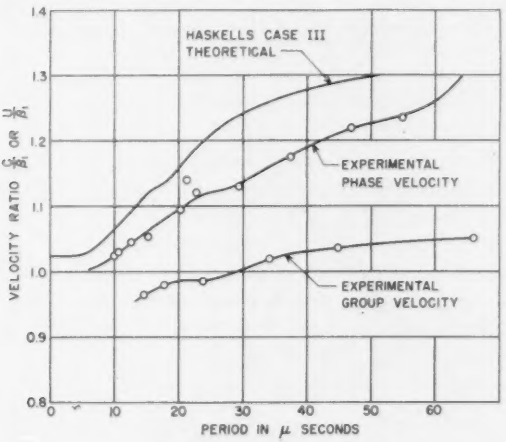



FIG. 6. Rayleigh wave phase and group velocity for a two layer crust (see upper Figure 5 for constants).

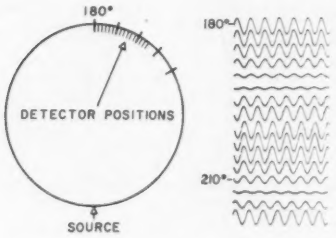



FIG. 7. Seismogram showing standing Rayleigh wave.

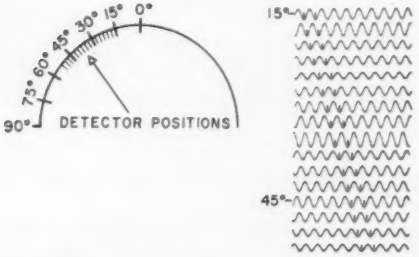



FIG. 8. Traveling Rayleigh wave from continuous source.

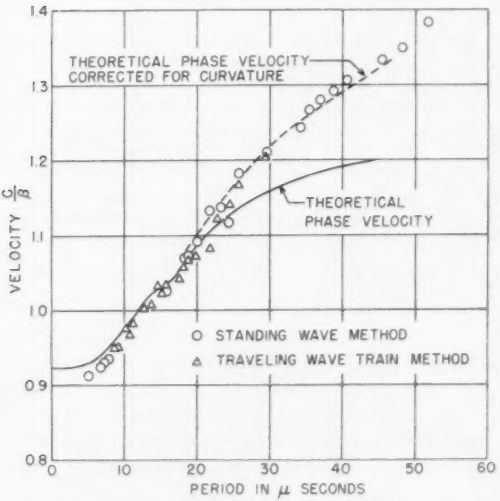



FIG. 9. Theoretical and experimental phase velocity (constants given in lower part of Figure 5).

between the theoretical and experimental results. Since the theoretical curve was for a half space it was necessary to apply a correction for the curvature of the disk model. An approximate correction was made for each theoretical phase velocity point by multiplying the phase velocity by a factor which would be correct for a homogeneous model. The correction for cylindrical curvature was originally given by Sezawa and later corrected by Oliver (Ewing, Jardetzky and Press, p. 265).

While these two methods give fairly good agreement with the theoretical phase velocity, it is desirable to improve these results further to distinguish the finer features of the phase velocity curve. Two additional methods were tried; the method of Brune and a Fourier analysis method. The precision of the Fourier analysis method indicates that a high accuracy can be achieved by this modeling technique, and the comparison of the four methods of phase velocity determination is a good illustration of an important problem that can be studied with this type of model. Brune's method, based on the stationary phase technique, makes use of the arrival times of peaks and troughs of the dispersed wave train to determine phase velocity (Brune, Nafe and Oliver, in press).

The Fourier analysis made use of the following relationship between the phase of a Fourier component at two distances:

$$C = \frac{(X_b - X_a)\omega}{\phi_b - \phi_a + 2n\pi} = \text{Phase Velocity}$$

$X_b$, $X_a$—are distances to points $a$ and $b$.

$\phi_b$, $\phi_a$—apparent phase angles of frequency component $\omega$ measured with respect to origin time.

$\omega$—angular frequency.

$$\frac{\phi_b - \phi_a + 2n\pi}{\omega} = \text{phase delay time between points } a \text{ and } b.$$

The seismograms in Figure 10 were digitized and subjected to a Fourier analysis on our electronic digital computer. This analysis yielded amplitude and phase of the Fourier spectral components. The latter was used to derive the experimental phase velocity dispersion curve (Figure 11). Excellent precision is obtained by this method as evidenced by the agreement between the experimental data and theoretical curves. The small bend in the theoretical curve at 17 micro/sec is indicated by the experimental phase velocities. The systematic discrepancy that does exist is less than one half of one percent and is well within the error expected from the inaccuracies in the machining process.

## CONCLUSION

This study shows the feasibility of constructing two-dimensional models in which a body velocity and density can be made to vary continually with depth.

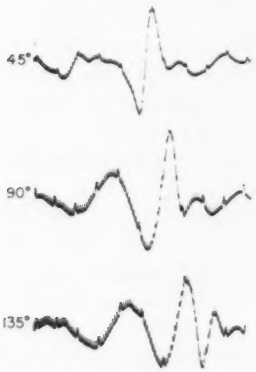



FIG. 10. Seismograms showing Rayleigh wave dispersions at three distances.

A successful test was made by comparing theoretical and experimental dispersion curves of Rayleigh waves in a double layered crust.

In future papers we will report on further applications of this modeling technique: (1) the effect of the low velocity upper mantle layer on body wave amplitudes (the shadow zone problem); (2) methods of deducing the properties of the source by operating on dispersed surface waves.

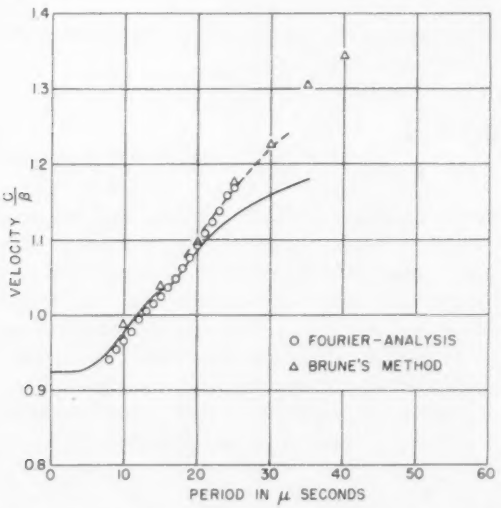



FIG. 11. Experimental dispersion curves according to Fourier analysis method and Brune's method together with theoretical curve. Dashed curve includes correction for curvature.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 998–1008, 5 Figs.

# VARIATION OF ELECTRICAL CONDUCTIVITY WITH DEPTH BY THE MAGNETO-TELLURIC METHOD*

E. R. NIBLETT† AND C. SAYN-WITTGENSTEIN†

ABSTRACT

Apparatus has been installed at the Dominion Observatory Research Station at Meanook, Alberta, for the continuous recording of earth potentials. The theory due to Cagniard (1953) and others, in which relative amplitudes of horizontal components of electric and magnetic fields are used to interpret the sub-surface structure, is applied in a modified form, to data from the Meanook records. Values of electrical conductivity between depths of 10 km and 100 km are estimated, and found to vary roughly between $10^{-13}$ and $10^{-14}$ e.m.u.

## INTRODUCTION

The Magneto-Telluric method of determining the electrical conductivity of the sub-surface strata is based on the fact that natural electromagnetic variations will penetrate into the earth to a depth which depends on their frequency and on the conductivity of the rock. By applying Maxwell's equations within the framework of certain rather broad assumptions it is possible to estimate conductivity as a function of depth from measurements of earth potential and magnetic field made at the surface.

The equations governing electromagnetic variations inside a solid conducting medium are:

$$\text{curl } \boldsymbol{H} = 4\pi j, \tag{1}$$

$$\text{curl } \boldsymbol{E} = -\frac{\partial \boldsymbol{H}}{\partial t}, \tag{2}$$

$$j = \sigma \boldsymbol{E}. \tag{3}$$

Here $H$ is the magnetic field vector, $E$ the electric vector, $j$ the current density, and $\sigma$ the electrical conductivity. All quantities are expressed in e.m.u. and the magnetic permeability is taken to be unity.

The induction problem inside the earth has been investigated by Kato and Kikuchi (1950), Rikitake (1951), Cagniard (1953), Tikhonov and Lipskaya (1952) and others. Most authors have assumed that horizontal gradients of the field vectors are negligible compared to the vertical gradients, and that time variations are periodic; i.e.

$$\partial/\partial x = \partial/\partial y = 0 \quad \text{and} \quad \partial/\partial t = -\frac{2\pi i}{T}, \tag{4}$$

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where the variables are expressed in terms of cartesian co-ordinates $(x, y, z)$ and $T$ is the period. The positive directions of the co-ordinate axes are true north, true east, and vertically downward respectively. Physically, these assumptions require the electrical conductivity to be a function of depth only, and the sources of field variation to be such that the horizontal extent of the phenomena at the surface is much greater than their penetration depth. It is clear that the horizontal gradients will be negligible only if

$$j_z \ll (j_x^2 + j_y^2)^{1/2} \quad \text{and} \quad \dot{H}_z \ll (\dot{H}_x^2 + \dot{H}_y^2)^{1/2}. \tag{5}$$

If (4) and (5) are valid, and if we take $\bar{\sigma}$ to represent the average or effective conductivity to a penetration depth $Z$, equations (1), (2), and (3) lead to the approximations

$$-\frac{H_y}{Z} \approx 4\pi\bar{\sigma}E_x, \qquad \frac{H_x}{Z} \approx 4\pi\bar{\sigma}E_y \tag{6}$$

$$-\frac{E_y}{Z} \approx \frac{2\pi i H_x}{T}, \qquad \frac{E_x}{Z} \approx \frac{2\pi i H_y}{T}, \tag{7}$$

in which the operator $\partial/\partial z$ has been replaced by $1/Z$ and $E_x$, $E_y$, $H_x$, $H_y$ refer to field variations of period T. From (6) and (7)

$$\bar{\sigma} \approx \frac{1}{2\left|\frac{E}{H}\right|^2 T}, \tag{8}$$

$$Z \approx \frac{1}{2\pi}\left|\frac{E}{H}\right| T, \tag{9}$$

where $|E/H|$ stands for the amplitude ratio $|E_x/H_y|$ or $|E_y/H_x|$.

If amplitude ratios can be measured for a series of natural periods it is possible to determine the variation of effective conductivity with depth from equations (8) and (9). Equation (8) is identical to the relation for $\bar{\sigma}$ derived more rigorously by other authors. The penetration depth defined by (9) implies an attenuation factor of $\frac{1}{2}$ instead of the usual $1/e$.

If we consider electrical conductivity to be a continuous and finite function of depth between the surface and the greatest penetration depth encountered we can write

$$\sigma = f(z), \tag{10}$$

and

$$\bar{\sigma} = \frac{1}{Z}\int_0^Z f(z)dz = \frac{1}{Z}\,g(Z) \tag{11}$$

represents the effective conductivity to the depth $Z$. Then

$$\sigma = \frac{dg(Z)}{dZ} = Z\frac{d\bar{\sigma}}{dZ} + \bar{\sigma}. \tag{12}$$

The value of conductivity at various depths can be estimated from (12) provided $\bar{\sigma}$ can be established as a known function of $Z$.

## MEASUREMENT OF ELECTRIC AND MAGNETIC FIELDS

At the Meanook station earth potentials are measured in north-south and east-west directions. The electrodes are lead sheets 8 ft×4 ft×$\frac{1}{4}$ inch laid horizontally at a depth of 8 ft in soil which is a mixture of sand and clay. The separation of the east-west electrodes is 1.60 km, while that of the north-south pair is 1.47 km. The north and east components of the horizontal geomagnetic field are measured by means of a fluxgate magnetometer. $E_x$ and $H_y$ are recorded together on a dual channel Brown self-balancing potentiometer, while $E_y$ and $H_x$ are recorded together on a similar instrument. The sensitivity can be varied from 20 mv to 2,000 mv full scale for earth potentials and from 50 gammas to 2,000 gammas full scale for the magnetics. The earth potential records are calibrated by means of a potentiometer; the magnetic records by comparison with standard photographic traces from La Cour variometers.

The resistance through the ground between a pair of electrodes varies with the moisture content of the soil but has never been found to be much in excess of 100 ohms. The input impedances of the earth potential recording circuits are greater than 20,000 ohms. Thus, very little current is drawn by the recording apparatus and changes in soil resistivity and contact resistances at the probes should not affect the recorded potential differences. When data were being collected for this analysis the chart speeds of the Brown recorders were either 6 inch per hour or 20 inch per hour. An effort was made to keep the sensitivities adjusted so that the magnetic and earth potential traces remained on scale and were subject to variations of roughly the same size.

## THE VARIATION OF CONDUCTIVITY WITH DEPTH AT MEANOOK

Continuous recordings of $E_x$, $E_y$, $H_x$, and $H_y$ were made throughout 1958 and from these estimates of the amplitude ratios $|E_x/H_y|$ and $|E_y/H_x|$[1] were obtained for periods ranging from about 40 sec to 1,000 sec. No attempt at harmonic analysis was made, but instances were selected on the charts when both $E$ and $H$ traces exhibited a fairly good sinusoidal wave form. The ratio of amplitudes was measured in each case and converted to e.m.u. Values of $E_x/H_y$ were grouped together according to their periods and averaged. The first group contained values with periods less than one minute, the next values with periods be-

[1] The vertical bars about $E/H$ will be omitted henceforth. It is to be understood that the ratios refer to modulus only. The effects of phase differences are not considered in this paper.

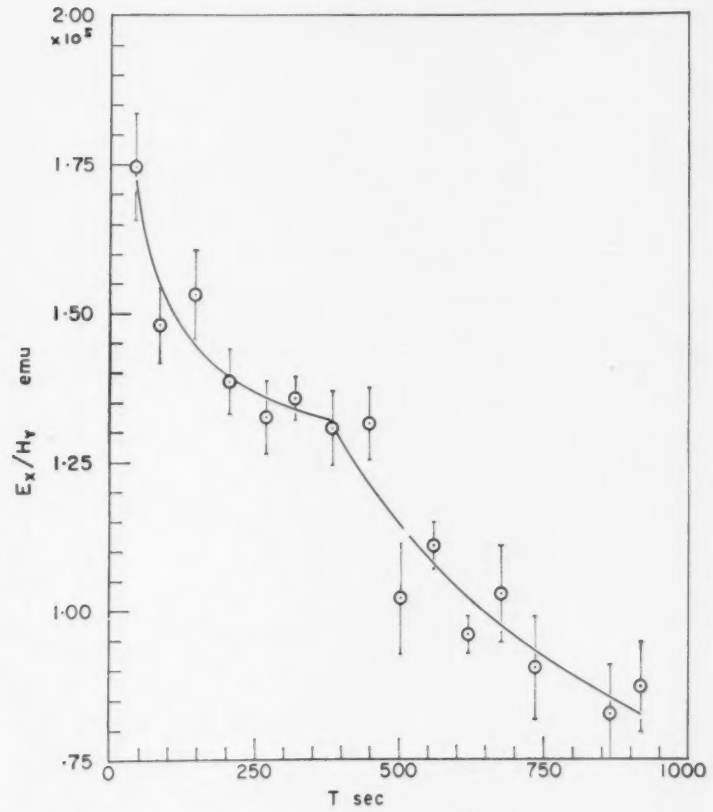


FIG. 1. Amplitude ratio $E_x/H$ vs period $T$.

tween one and two minutes, and so on. The data in $E_y/H_x$ were handled in the same manner. The results are shown in Figures 1 and 2 where average ratios are plotted against average periods. The scatter in the individual values of the ratios within a group is usually quite large. The standard errors of the means are shown; for the most part they lie between 5 percent and 10 percent. The average number of observations within a group is 42, though the number is larger than this for periods less than 400 sec and smaller for longer periods.

Equation (8) indicates that if $\bar{\sigma}=\sigma=$ constant the amplitude ratio can be expressed

$$\frac{E}{H}=\frac{B}{\sqrt{T}}$$

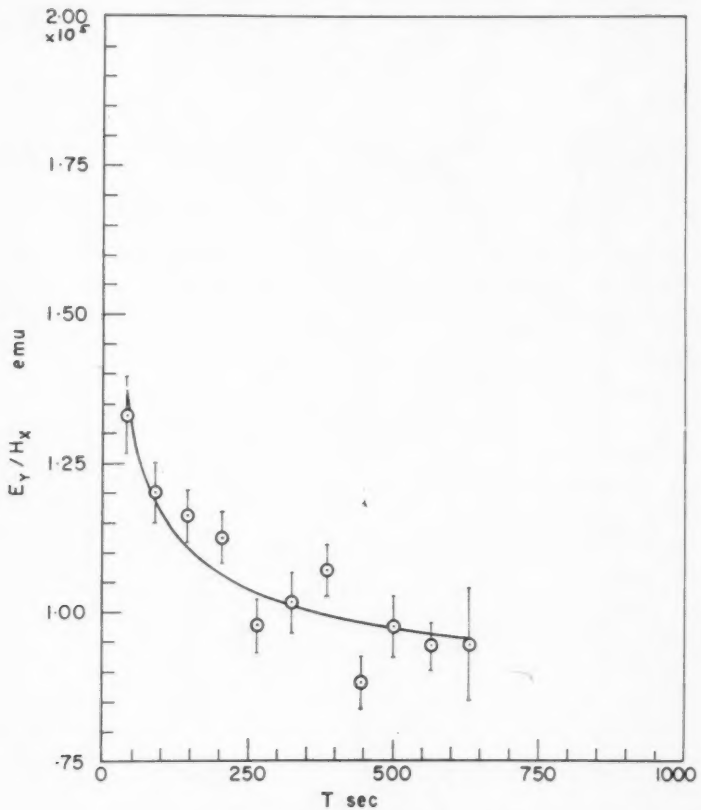


FIG. 2. Amplitude ratio $E_y/H_x$ vs period $T$.

where $B$ is a constant. In this case a plot of $E/H$ vs $1/\sqrt{T}$ should yield a straight line through the origin with slope $B=1/\sqrt{2\sigma}$. Plots of this type are shown in Figure 3. It is clear a straight line through the origin will not provide a reasonable fit to either set of data, and that the conductivity must be subject to appreciable variation throughout the range of depths which are appropriate.

Figure 3 does suggest that the $E_x/H_y$ data might be adequately fitted by two straight lines, and the $E_y/H_x$ data by a single straight line. The equations are of the form:

$$\frac{E_x}{H_y} = A_1 + \frac{B_1}{\sqrt{T}} \text{ in the range 0.051 to 0.150 of } T^{-1/2}$$

$$\frac{E_x}{H_y} = A_2 + \frac{B_2}{\sqrt{T}} \text{ in the range 0.033 to 0.051 of } T^{-1/2}$$

$$\frac{E_y}{H_x} = A_3 + \frac{B_3}{\sqrt{T}} \text{ in the range 0.040 to 0.158 of } T^{-1/2}.$$

The constants were determined by least squares and are:

$$A_1 = \quad 1.109 \times 10^5 \qquad B_1 = 4.11 \times 10^5$$
$$A_2 = -\,0.073 \times 10^5 \qquad B_2 = 27.2 \times 10^5$$
$$A_3 = \quad 0.815 \times 10^5 \qquad B_3 = 3.50 \times 10^5.$$

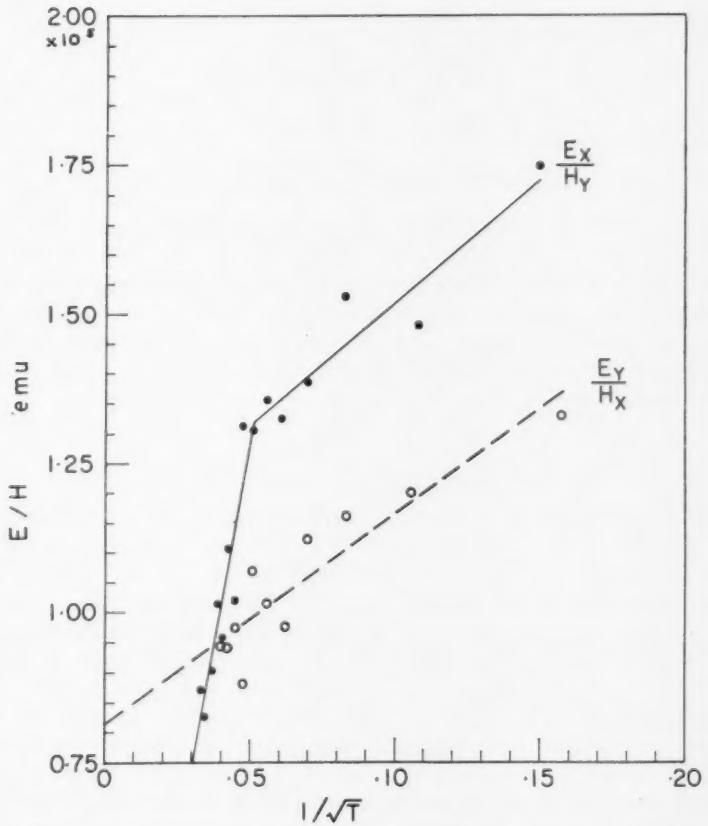


FIG. 3. Amplitude ratios vs $T^{-\frac{1}{2}}$.

The three computed straight lines are shown in Figure 3. Application of the "chi-square" test to the residuals indicates in each case that the linear representation is adequate for the data. The smooth curves of Figures 1 and 2 are obtained by plotting the computed values of $E/H$ against $T$ instead of $T^{-\frac{1}{2}}$.

Since we now express amplitude ratios in the form

$$\frac{E}{H} = A + \frac{B}{\sqrt{T}},$$

equations (8) and (9) become

$$\tilde{\sigma} = \{2(A^2T + 2AB\sqrt{T} + B^2)\}^{-1}, \tag{13}$$

and

$$Z = \frac{1}{2\pi}(AT + B\sqrt{T}). \tag{14}$$

These give, on elimination of $T$

$$16\pi^2A^2Z^2\tilde{\sigma}^2 - (8\pi AZ + 2B^2)\tilde{\sigma} + 1 = 0. \tag{15}$$

Equations (13), (14), and (15) hold only in the specified ranges of $T^{-\frac{1}{2}}$.

The effective conductivity is plotted against penetration depth for both cases in Figure 4. Values derived from the observations are shown for comparison with the curves computed from equations (13) and (14). The discontinuity in the curve computed from the $E_x/H_y$ data at $Z = 80$ km. corresponds to the intersection of the two straight lines in Figure 3.

From (12) and (15) we derive

$$\sigma = \frac{B^2\tilde{\sigma}}{B^2 + 4\pi AZ(1 - 4\pi AZ\tilde{\sigma})}. \tag{16}$$

The final curves showing conductivity as a function of depth are given in Figure 5.

## DISCUSSION

It is important to consider the validity of the initial assumption that horizontal gradients of the field vectors are negligible compared to the vertical ones. Horizontal gradients can arise in two ways. Appreciable variation of electrical conductivity or magnetic susceptibility over horizontal planes at the depths considered would lead to field gradients of internal origin. Furthermore, overhead current systems in the ionosphere may be neither sufficiently remote nor of suitable configuration to produce transient variations at the surface which are uniform over horizontal distances up to 100 km. At Meanook the latter effect is likely to be important because the station is close enough (5 degrees in geomagnetic latitude) to the auroral zone for the magnetic activity to be subject

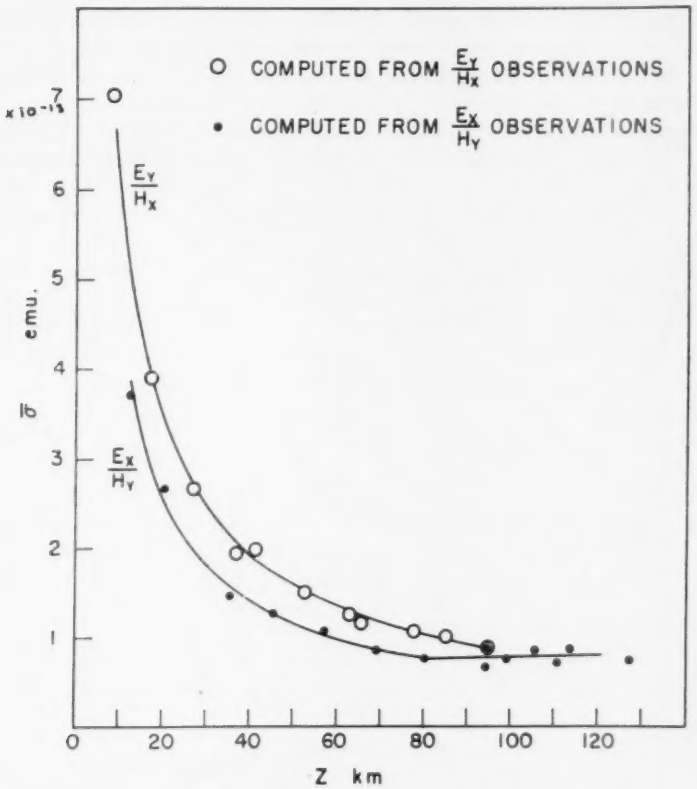


FIG. 4. Effective electrical conductivity $\bar{\sigma}$ vs depth $Z$.

to fairly rapid variation along the magnetic meridian. Since auroral zone currents are believed to occur at heights of the order of 150 km the transient field variations at the surface could vary considerably over a distance of 100 km particularly in the magnetic north-south direction.

From (5) it is evident that periodic field variations will have negligible horizontal gradients if

$$\frac{|H_z|}{\sqrt{|H_x|^2 + |H_y|^2}} \ll 1. \tag{17}$$

Since the only vertical force records available at Meanook are standard run magnetograms with sensitivities and chart speeds which are much less than those of the Brown recorders, a direct comparison between the amplitudes of vertical

and horizontal force variations is not possible. However, hourly ranges of $H_x$, $H_y$, and $H_z$ at the times when individual estimates of $E_z/H_y$ and $E_y/H_x$ were made were scaled off the standard run magnetograms. It was found that the ratio of hourly range activity in vertical force to hourly range activity in horizontal force varied from 0.1 to 2.5, the average value being 0.56. This gives a crude indication that for the longer periods the amplitude ratio of (17), while

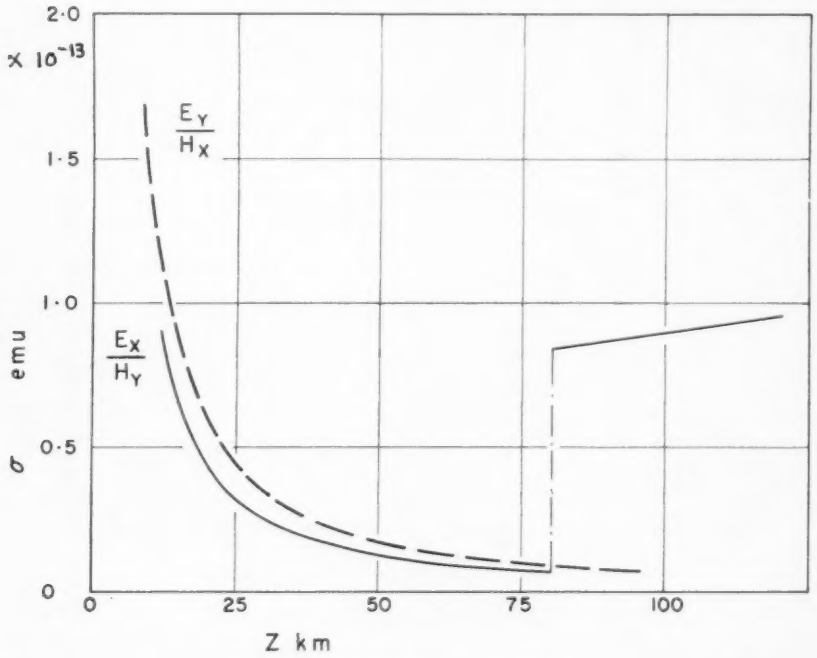


FIG. 5. Electrical conductivity $\sigma$ vs depth $Z$.

subject to considerable variation, has an average value of the order of $\frac{1}{2}$. If this is the case, the horizontal gradients may be generally smaller than the vertical ones, but not small enough to be considered negligible.

Figures 1, 2, and 3 reveal that values of $E_z/H_y$ are, in general, quite different from $E_y/H_x$ at corresponding values of the period $T$. The discrepancies are too large to be explained by errors in the measurement of amplitudes, and it is again concluded that the conditions of horizontal uniformity imposed by setting $\partial/\partial x = \partial/\partial y = 0$ do not closely approximate actual conditions in the Meanook region. None the less, each set of data gives electrical conductivities which agree to within a factor of two between depths of 10 km and 80 km. The conclusion

that the curves of Figure 5 show the correct order of magnitude and the general trend of the variation in this range seems justified.

A sudden increase in $\sigma$ from $10^{-14}$ e.m.u. to $10^{-13}$ e.m.u. at 80 km is indicated by the $E_x/H_y$ data. The discontinuity was forced into the curve when it was decided to fit two straight lines to these data as in Figure 3. This is much the simplest method of obtaining an analytical expression. A smooth curve of the form

$$\frac{E_x}{H_y} = A + \frac{B}{\sqrt{T}} + \frac{C}{T} + \cdots$$

could be fitted, but a function of at least 3rd degree in $T^{-\frac{1}{2}}$ would be required. Such a procedure is scarcely worth while. The conductivity must increase by roughly an order of magnitude between 60 km and 100 km to be consistent with the $E_x/H_y$ data at longer periods. A smooth curve would only replace the discontinuity at 80 km by a fairly rapid rise in this region. Since condition (17) is most unlikely to be fulfilled at longer periods, and in the absence of corroborative evidence from the $E_y/H_x$ data, it is far from certain that this rise in conductivity is real. The best that can be said is that a rise at about 80 km is not inconsistent with the $E_y/H_x$ values plotted in Figure 3. However, good estimates of this ratio were not obtained at long enough periods to establish a significant trend at depths close to 100 km.

Surface values of $\sigma$ vary from about $10^{-11}$ e.m.u. for sea water to $10^{-16}$ e.m.u. and less for certain types of dry earth and rock. An estimate of the surface conductivity can be obtained by extrapolating the conductivity depth curves of Figure 5 to $Z=0$. This is equivalent to putting $Z=0$ in equation (15) from which we derive $\tilde{\sigma}_0=\sigma_0=1/(2B^2)$. The extrapolated values are $\sigma_0=3\times10^{-12}$ e.m.u. for the $E_x/H_y$ data, and $\sigma_0=4\times10^{-12}$ e.m.u. for the $E_y/H_x$ data.

In the Athabasca region, the Precambrian basement is overlain by Devonian and Cretaceous sediments to a depth of about 1.8 km. These rocks are predominately shales, sandstones, dolomites and limestones. Their conductivity, even allowing for moisture content, is unlikely to exceed $10^{-13}$ e.m.u. The extrapolated surface values appear to be high by at least an order of magnitude. The most likely explanation is that the computed conductivities decrease too rapidly with depth in the neighborhood of 10–15 kms. The curves would probably be subject to modification at these depths if the range of $E/H$ determinations could be extended to periods of 10 sec or less.

There have not been many previous estimates of electrical conductivity at depths between 10 and 100 kms. Coster (1948) measured the conductivity of several rock samples at various temperatures up to 1,000°C. His conclusion that the conductivity at 100 km below the surface would be about $10^{-13}$ e.m.u. agrees well with the present result. He also notes that the conductivity would be expected to decrease over the first few kms below the surface as the rocks become progressively drier. At greater depths (and higher temperatures) the conductivity should increase as a consequence of the semi-conduction process in

the basic rocks of the mantle. Lahiri and Price (1939) made estimates to a depth of about 1,500 km by comparing the induced fields of magnetic daily variation and storm time variation to their inducing fields. They concluded that the mean conductivity of the earth down to 600 km is about $2\times10^{-13}$ e.m.u., and that at some regions near the surface the value must be higher than this. However, they account for their high surface value by treating the upper layer as a uniform ocean having a depth of about 1 km. With this interpretation the conductivity of the solid earth below would not exceed $10^{-15}$ e.m.u. to depths of 200 or 300 km. Rikitake (1950) adopts a similar figure for this range. While a high surface value is certainly indicated in the present analysis, the oceans are much too remote to affect the result. Between 10 and 100 km the estimated values are between one and two orders of magnitude higher than the one adopted by Lahiri and Price and Rikitake.

ACKNOWLEDGMENTS

The operation and maintenance of the earth potential and magnetic recording apparatus was capably handled by Miss A. B. Cook and Mr. G. L. Carr at Meanook Observatory. We are indebted to Mr. R. G. Madill, Dr. K. Whitham, and Dr. J. A. Rottenburg for their advice on numerous occasions.

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1009–1022, 19 FIGS.

# OPERATIONS RESEARCH—A TOOL IN OIL EXPLORATION*

HOWARD COBB†

## ABSTRACT

Operations Research is a tool which may be used by the exploration man to help in planning exploration activities and in making decisions. Electronic computers and mechanized data handling may be used in the analyses which are a part of Operations Research. Various types of exploration data which we put on punch cards are readily available for Operations Research studies. Mathematical models of various activities play a large role. They are often built up from data of past experience. Thus, statistics and probability theory are important to the studies. Other techniques commonly associated with Operations Research studies are Linear Programming, Game Theory, Queueing Theory, Monte Carlo, and Search Theory. Operations Research has been defined as quantitative common sense. It is probably the cheapest and one of the more effective of our exploration tools. We use it when we plan optimum control for a geophysical survey. We use it when we analyze the future of a frontier oil province.

## INTRODUCTION

Today, we can process and present geophysical and geological data at great speed, using our high speed computers and plotters. As their use increases in the coming years the entire oil exploration process will accelerate. This acceleration in the exploration process will demand faster decisions. Moreover our current economic atmosphere demands more exact decisions in oil exploration.

The methods of operations research can provide data for more exact decision-making. Our computers and punched-card files can provide some of the analyses of operations research at great speed.

The purposes of this paper are to define operations research, describe its methods and consider briefly some exploration problems in that field.

Operations research has been defined as a scientific method of providing management with a quantitative basis for decisions regarding the operations under its control (Morse and Kimball, 1958, p. 1). The prime characteristics are stated in Figure 1. It will not make decisions, but it may assign probabilities of certain results in case a particular course of action is chosen. Operations research is an applied science which was used effectively in planning military operations during World War II. Since the war it has had many uses in industry. It attempts to estimate the uncertainties in its predictions of the results of taking various courses of action.

Operations research analyzes operational problems ranging from the simplest to the most complex, using all known scientific techniques available to the problem. Solutions to the simplest problems often have proportionately larger payoffs. As a relatively simple problem we may quantitatively determine the

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OPERATIONS RESEARCH

√IMPLIES ORGANIZED ACTIVITY
√IMPLIES RECOGNIZED ACTIVITY
√ALL SCIENTIFIC TECHNIQUES AS TOOLS
√ALWAYS QUANTITATIVE
√DOES NOT MAKE DECISIONS

FIG. 1. The characteristics of operations research.

optimum density of control for a geophysical survey by analyzing its cost relative to its effectiveness. An example of a complex problem is that of devising a mathematical model of the operations of an entire corporation. Using such a model as a guide to planning the operations of the corporation might require the use of a larger computer.

OIL FAVORABILITY

Usually, the essence of a study in operations research is that of determining a formula for the effectiveness of the operation in terms of the variables of the operation, then using this formula to guide the operation. Figure 2 gives the general formula. Suppose we apply the formula to an exploration situation. We

$$E=f(X_i)$$

$E$: EFFECTIVENESS OF THE OPERATION
$X_i$: VARIABLES OF THE OPERATION

FIG. 2. The general formula for the effectiveness of an operation.

ask how favorable ($E$) a recommended area is in the light of certain geological and geophysical conditions ($X_i$) which we know exist there. We are asking what is the probability that the area will be productive. Instead of a dozen maps showing seismic structure, gravity anomalies, subsurface, facies, etc., we would have just one map contoured in terms of oil favorability. Perhaps we will never devise such a map. Nonetheless it is desirable to quantitatively assess each item of information, if at all possible.

Figure 3 gives a rather nebulous formula for the favorability at a particular

AREA FAVORABILITY = FUNCTION OF:

GEOLOGICAL FAVORABILITY
(ENTIRE SECTION)
GEOPHYSICAL FAVORABILITY
(ALL METHODS)
OTHER FAVORABILITY

FIG. 3. A formula for area favorability.

location. It is a function of the favorabilities for all geologic horizons, of all geophysical information and other contributions. Now we need some common denominator by which we may express these favorabilities.

Let us assume that we have made statistical studies of our past experience which indicate that a certain stratigraphic condition has a 25 percent chance of producing. Our studies may also show that gravity anomalies of a certain type have a 25 percent chance of producing. Now we have come closer to expressing stratigraphy and gravity anomalies in the same units. We have made a study in operations research.

Our most serious problem in making such studies is that of collection of data. We have large files of oil exploration data. But not all of the data for our local area is in one file. No one person has knowledge of it. There may be a missing link which would have provided the idea leading to the discovery of an oil field.

As more and more of our exploration information is punched on cards this problem will not be so serious. The data will be readily available for data plotters, and for computations and statistical analyses by computers. Consider our geologic data, Figure 4. Punched on cards, computers could process facies data, for example, and plotters could furnish the geologist with a particular map which he would not normally have time to construct. It might provide the missing link.

Figure 5 illustrates a favorable geologic situation. Convergence and truncation of an objective horizon give a favorability high. After truncation, that formation's favorability is zero. Figure 6 shows the map in this area. From punched card data our plotters can plot data for an isopach map on which the zone of high favorability is outlined. We may note a regional gravity high paralleling the regional zone of convergence. Statistical studies may indicate a certain probability that the area will be productive. They may indicate a certain small probability that a very large oil field lies in the area. Dad Joiner discovered this one, Figure 7, without the benefit of capital, geology, geophysics, electronic computers or operations research. He did have an abundant share of one other necessary asset which contributed to the total favorability of oil finding in the area.

## A MATHEMATICAL MODEL FOR PREDICTING EXPLORATION SUCCESS

Mathematical models play a large role in operations research studies. They are often built up from data of past experience. Thus, statistics and probability theory are important to the studies.

Figure 8 gives the formula for one such model. As more and more wildcats in an area test a formation, discovery success will become less because there will be less new fields to find. Finally, in the last stages the success ratio, the slope of the curve, will approach zero. The formula is a probabilistic model which gives the number of fields, $N$, of a particular class, which are discovered by drilling $n$ wildcats. $N_0$ is the total ultimate number of fields of that class. $C$ will depend on the type of exploration used, e.g. seismic, random drilling, etc.

As our electronic data-mechanization improves, the statistical data could be readily available to construct such models. This model may be used in two ways:

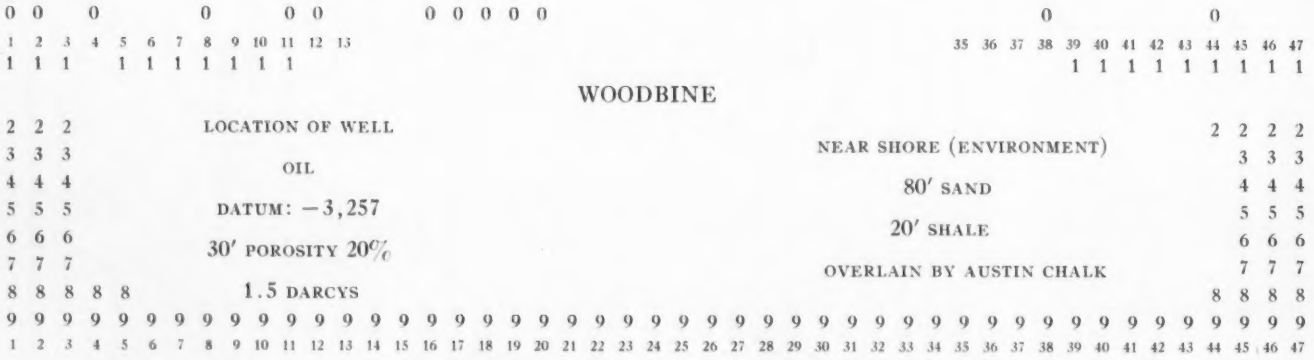


FIG. 4. Oil exploration data on punch cards.

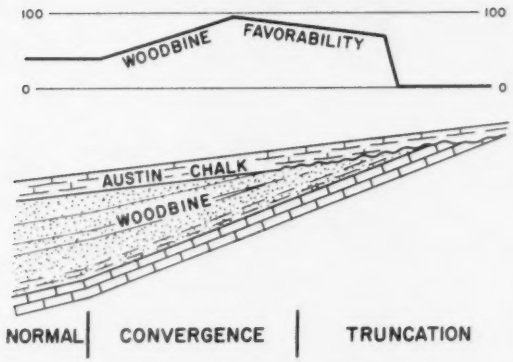


FIG. 5. Cross-section of a favorable geologic situation.

(1) As exploration progresses in an area, $C$ and $N_0$ may perhaps be estimated for each formation from the historical data. The model may then be used to determine the success-ratio at any future stage of the exploration process.

(2) We may use it to appraise a frontier basin by using data from fully-prospected, geologically similar areas which have objective formations of similar characteristics. Our statistical data may indicate the probable numbers of fields of various sizes to be expected. From the data we can arrive at a probable value for the reserves of the basin. Our statistical data may allow us to define confidence intervals within which the true values will almost surely lie. As exploration continues in the frontier area we will of course revise our model to fit the facts.

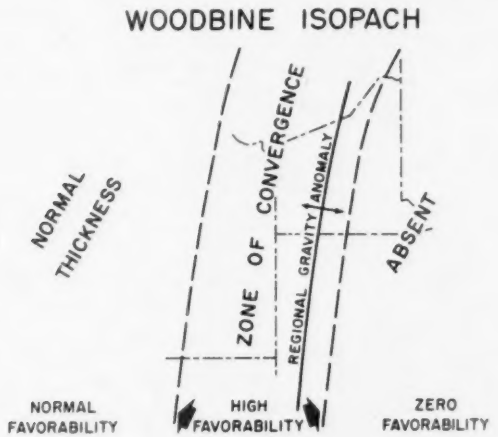


FIG. 6. Map showing the favorable geologic situation.

FIG. 7. An oil discovery.

Such a model will suffer from the usual limitations and uncertainties attached to statistical models. It is difficult to get precise data concerning geologically similar, fully-prospected areas.

For example, fields have a habit of expanding in estimated reserves over the years. Figure 9 shows frequency distributions, by reserves classes, of 104 fields which were estimated to have more than five million bbl ultimate reserves in 1944. The same 104 fields were used to plot the distributions of the reserves estimates at 5-year intervals. The distributions shift sharply upward over the 15 years. Figure 10 shows the change in total estimated ultimate reserves for these 104 fields over the 15-year period.

Despite the inherent weaknesses of such a probabilistic exploration prediction model, a judgment based on quantitative data available will likely be better than judgment based largely on an intuitive basis.

Some interesting studies using probabilistic models appear in the literature. J. J. Arps and T. G. Roberts (1958) used a model of the type we have just de-

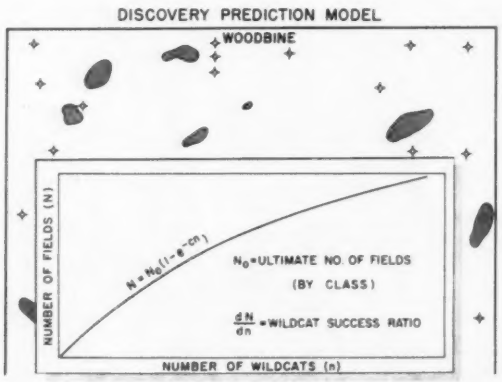


FIG. 8. A mathematical model for predicting exploration success.

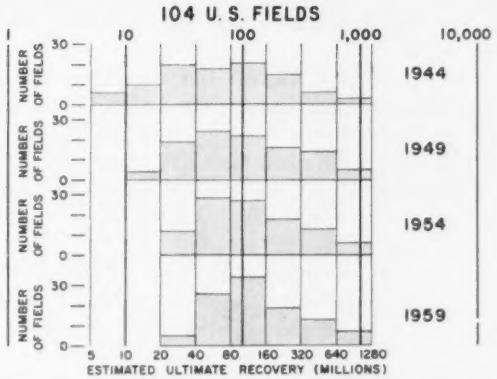


FIG. 9. Frequency distribution of estimated ultimate reserves of 104 U. S. fields, by reserves classes, at 5-year intervals.

scribed to study the economics of drilling for Cretaceous oil in the Denver-Julesburg Basin. M. Allais (1956, 1957) in France used a probabilistic model to appraise the mining prospects of the Algerian Sahara. L. B. Slichter (1955) made an analysis of optimum drilling patterns for ore to obtain the highest profit ratio. R. M. Ellis and J. H. Blackwell (1959) extended Slichter's theory. These are excellent examples of studies in operations research.

## OPERATIONS RESEARCH MODELS

Mathematical models of various phases of operations in industry have been constructed by various companies. Often, electronic computers may be used to advantage in their processing. A mathematical model may be defined as a formula which expresses the effectiveness of the system in terms of the variables,

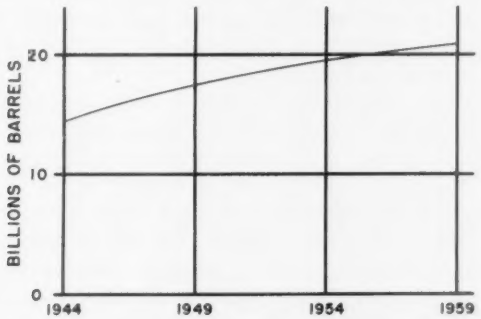


FIG. 10. Total estimated ultimate reserves of 104 U. S. fields at 5-year intervals.

some of which are subject to control, others which are not (Churchman, Ackoff and Arnoff, 1957, p. 13).

If operations are expensive, a quantitative analysis of the results of taking alternative courses of action may be as profitable as, for example, equal effort given to building new instruments. A good model will predict how changes in the system will change its effectiveness. If an effective model can be programmed for the electronic computer it may tell in a few hours some of the results to be anticipated by a year's risky operations. It may show where changes should be made.

Figure 11 illustrates the definition of the model. The first term of the equation gives the system's effectiveness; the other terms are the variables of the system. In order to solve this model we would need to express mathematically

EXPLORATION SUCCESS=
$f$ (MEN+MONEY
+INSTRUMENTS
+METHODS
+TECHNOLOGY
+ORGANIZATION
+MANAGEMENT)

FIG. 11. Oil exploration model.

each element's contribution to the effectiveness of the system. This model is perhaps too all-inclusive. We will be likely to build more elementary models for such activities as seismic exploration, gravity exploration, geologic exploration, leasing, etc.

### GEOPHYSICAL MODEL—THE EFFECTIVENESS OF A GEOPHYSICAL SURVEY

For the model of a geophysical survey we need to express the effectiveness of the survey in terms of such variables as cost, type of control, and others. How may we determine the effectiveness of a geophysical survey? One definition is in terms of barrels of oil found per dollar spent.

Figure 12 gives the formula for the cost of a survey in terms of loop dimensions, station spacing on lines, the size of the survey and the cost per station. In this figure, cost is plotted as a function of the loop dimension for a particular case. Note that the cost curve becomes quite steep as the loop dimension decreases. Since cost is an important factor to effectiveness, this equation tells us to plan carefully the control needed. Figure 13 shows the cost curve as a function of station spacing. Note that this curve becomes quite steep at spacing of one fourth mile, which is a common spacing for geophysical surveys.

Optimum loop dimension depends on the frequency distribution of structures as to areal size. Thus the survey effectiveness may be considerably increased by

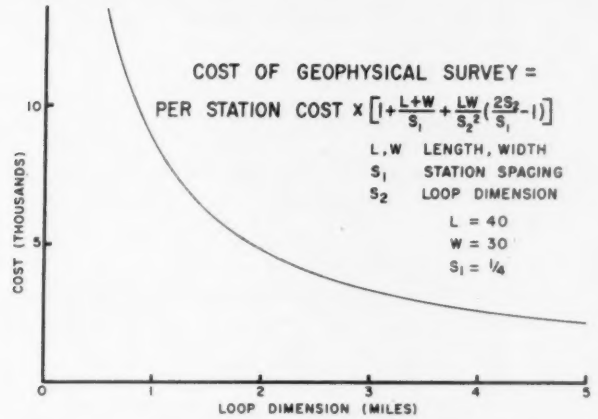


FIG. 12. The cost of a geophysical survey as a function of loop dimension.

planning the survey to map only those structures which have reasonably large areas.

Let us now turn specifically to the gravity method to illustrate some things we would need to analyze to construct the gravity model. Gravity anomalies of deep structures are broader than those of shallow. Figure 14 shows the gravity effect of a sphere or point mass. Its width at half value equals 1.54 times the depth to its center. Masses of all other shapes give broader anomalies than does the sphere. If we know the depth of the significant density contrast, as given by a densilog, (see Figure 15) we may choose the loop dimension so that at least one line crosses the anomaly at, for example, greater than half value.

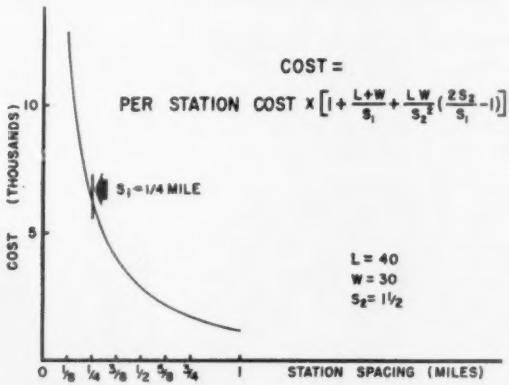


FIG. 13. The cost of a geophysical survey as a function of station spacing.

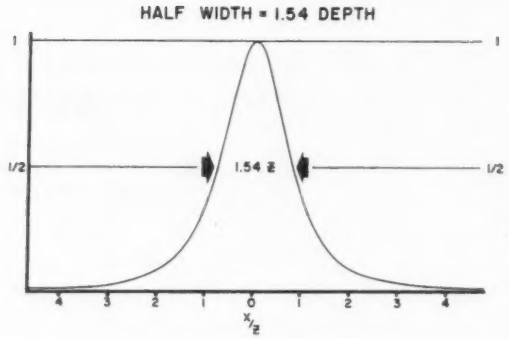


FIG. 14. The gravity effect of a sphere or point mass.

Another measure of the effectiveness of the survey is what proportion of the oil structures the method is sensitive enough to map. Figure 16 shows the distribution of the number of oil fields as a function of the magnitude of the residual gravity anomaly in a Gulf Coast area. Gravity successfully shows most salt structures in this area as residual minima.

However, the figure shows that a number of oil fields fall on residual maxima, and these are not associated with cap rock. We have an ambiguity both for the gravity interpreter and for our operational model. In Figure 17 we try to partially resolve this ambiguity by showing the distribution of reserves for those fields which have estimated reserves greater than five million bbl. These present-day statistics indicate that the bulk of the reserves in this area are associated with structures which produce residual minima.

In some areas there is a question as to whether there is any association between anomalies and oil fields. This would imply zero effectiveness. Figure 18

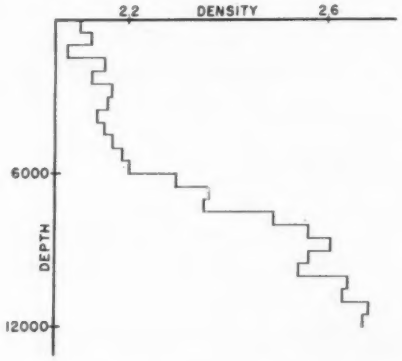


FIG. 15. Density vs. depth.

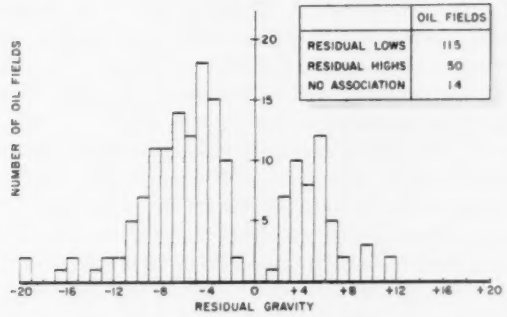


FIG. 16. The distribution of the number of oil fields as a function of the magnitude of the residual gravity anomaly in a Gulf Coast area.

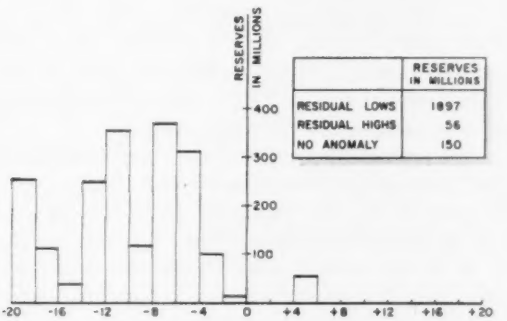


FIG. 17. The distribution of reserves as a function of the magnitude of the residual gravity anomaly for those fields which have estimated reserves greater than 5 million bbl.

| FREQUENCY | CONDITION |
|---|---|
| $N_1$ | OIL FIELD PRESENT, ANOMALY ASSOCIATED |
| $N_2$ | OIL FIELD ABSENT, ANOMALY PRESENT |
| $N_3$ | OIL FIELD PRESENT, ANOMALY ABSENT |
| $N_4$ | OIL FIELD ABSENT, ANOMALY ABSENT |

IF NO ASSOCIATION: $N_1N_4 = N_2N_3$

FIG. 18. A test of association between geophysical anomalies and oil fields.

gives a test which may tell whether there is association; and further statistical analysis may indicate the degree and certainty of the association. This test would likely not be successful, however, in its present form, in an area where we consider that structures may be associated with both maxima and minima.

We may continue our study of the effectiveness of the gravity survey by collecting statistics in prospected areas concerning how close the center of production lies to the center of the gravity anomaly. These data could also be analyzed as a function of loop dimension. They would determine how large a seismic area it would be necessary to work to evaluate the gravity anomaly.

Such studies as these which we have described would be incorporated in constructing our gravity model. The model would be of use for future operations in the area for which it was constructed, or in geophysically similar areas. Similar models may be constructed for other exploration activities.

## TECHNIQUES OF OPERATIONS RESEARCH

Analyses of operations research, some examples of which we have briefly described, tell something of the effectiveness of our various exploration activities. Models may furnish quantitative data to use as a basis for allocating funds to those activities.

Figure 19 lists techniques commonly associated with the methods of operations research. They may or may not be included in the model of the activity. A given problem is likely to involve more than one of these.

Linear programming and other types of mathematical programming are used in a wide variety of problems in industry which require optimization. These techniques are suited to certain allocation problems. An example will serve to illustrate the use. In 1945 George Stigler alarmed by the rising cost of living, used the technique to determine the adequate diet of minimum cost. The 9 nutrients necessary to healthy subsistence could be obtained from 77 common foods. Stigler showed that the total cost of the minimum diet for the year 1944 was \$59.88, up 50% from the 1939 cost of \$39.93. This 1944 diet, determined by linear programming, consisted mainly of wheat flour, cabbage and hog liver. Mathematical programming techniques may be helpful in telling how to combine our resources (men, money, equipment, etc.) with our activities (seismic, drilling, gravity, leases, etc,) to maximize overall exploration effectiveness.

Statistics and probability theory, we have seen, are important to many, per-

√LINEAR AND MATHEMATICAL PROGRAMMING
√STATISTICS AND PROBABILITY THEORY
√GAME THEORY
√QUEUEING THEORY
√SEARCH THEORY AND OPTIMUM DISTRIBUTION OF EFFORT
√MONTE CARLO

FIG. 19. Techniques of operations research.

haps most, phases of operations research. They appear prominently in the models.

Game theory, and the related theory of bidding, are mathematical models in which the factors of competition are reduced to their simplest elements. The effectiveness of our exploration effort, in terms of profit, will be affected by the actions of our competitors. As in a game the outcome is determined by the multiple choices of the strategies of the competitors. Consider bidding as an example. If we commonly play poker with the same group we could possibly determine the pattern of their betting. We may determine a distribution curve for each which would give probabilities of their betting lower or higher than our estimation of what is warranted. We could perhaps establish confidence intervals regarding the strengths of the hands around the table. Bidding theory is used in competitive bidding activities in industry. One useful application of this theory lies in the field of bidding for oil concessions and government tracts.

Queueing theory (Marshall, 1954) is the theory of waiting lines. Early work was done by our friends, the British. It has been speculated that the reason for this is that there is no more stimulating time to analyze queues than while one is standing in one. Oil companies hold properties in need of processing for varying periods. Fifteen acres are held under lease in the U. S. for every acre presently proved productive (The Oil Producing Industry In Your State, 1959). The cost of holding vs that of prompt action may be an important matter for analysis. A mathematical model of leasing activities could possibly aid in the analysis.

A considerable amount of search theory and theory concerned with the optimum distribution of effort was formulated during World War II (Morse and Kimball, 1958, Koopman, 1956, 1957). The search for oil fields is similar in many respects to the search for submarines and this theory may be of help in operations research studies in oil exploration.

The Monte Carlo technique is essentially a random sampling procedure. The models of operations research often contain probability distribution functions. Our past experience may often be expressed in the form of empirically determined probability distributions. Monte Carlo allows a simulation of an operation often based on data from our past experience. Electronic computers may be programmed to generate random numbers, thus represent those probability distributions, incorporating Monte Carlo with the model.

## CONCLUSION

Someone has defined operations research as quantitative commonsense. Each of us uses it every day to varying degrees. We will be more successful in finding oil if we analyze every exploration situation, not by hunch, but quantitatively insofar as possible. We should use the special mathematical techniques of operations research if we find they are applicable. We should quantitatively analyze our past experience, because "What is past, is prologue."

The mathematical analyses developed by operations research studies will be

submitted to the exploration manager. He knows of quite a few intangibles of the problem that the mathematician did not know about. He will inject these intangibles, then use his exploration experience and imagination to make his decision.

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1023–1034, 11 FIGS.

# GRAVITY OPERATIONS IN GUATEMALA*

L. L. NETTLETON† AND PAUL ELKINS†

## ABSTRACT

This paper describes the logistics and field methods used for a gravity survey over a large concession in the northwest corner of Guatemala. Almost the entire network of lines for gravity stations was cut through heavy jungle and heliports were cut at line intersections. Logistics of the operation were heavily dependent on aircraft, using helicopters for transportation from camps to heliports, amphibian aircraft from main base to field camps and chartered DC-3 aircraft from Guatemala City to main camp. Field conditions and operations are illustrated by photographs. Statistics of operation and station production are included but no gravity data are shown.

## INTRODUCTION

This paper gives a general review of operational procedures and resulting gravity station production from an extensive gravity meter survey in an uninhabited jungle area. Because of the almost complete lack of roads or waterways and the coverage by a dense tropical forest, this was a most difficult survey. It is hoped that a discussion of the manner in which the problems were met to achieve a generally satisfactory coverage of the assigned area may be of interest and also may assist others in the exploration industry who may be called on to work in similar areas.

## AREA, PROGRAM AND LOGISTICS

The area of the survey is in the northwest corner of Guatemala (Figure 1). The village of Carmelita, just south of the survey area, has an airstrip which is serviced more or less regularly by scheduled flights of Aviateca, the Guatemalan Government airline, using DC-3 aircraft. Service is interrupted by very wet weather because the airstrip then becomes too soft for use. There is no usable road to Carmelita, and all personnel and supplies were brought in by air from Guatemala City, a distance of approximately 325 km (200 mi).

Within the area of the survey, the only lines of communication are two mule trails north from Carmelita, one of which extends to the Mexican border. There is also a trail (outside the survey area) which has been widened into a tractor road, for seismic operations, which extends southwesterly from Carmelita to the southeastern part of the concession. The region is almost unpopulated and not more than 20 families live in the entire area worked. The only economic resources are chicle and some mahogany. The chicle sap is gathered during the rainy season (September through December). The native chiclero can gather about 100 lb of chicle a week and earns a wage of about 25 quetzales (approximately equivalent to dollars).

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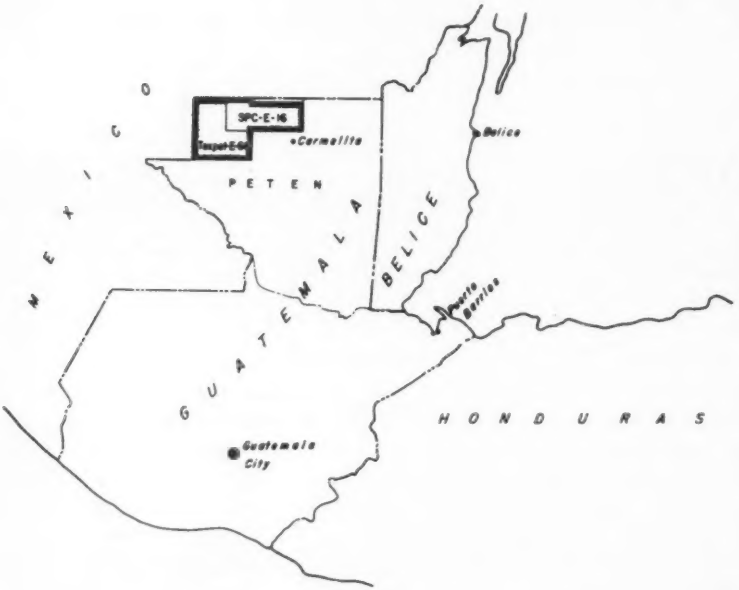


FIG. 1. Index Map, showing area of operation.

The present, almost unpopulated and abandoned status of the country apparently is very different from that of some centuries ago when a relatively advanced civilization thrived there as shown by numerous Mayan ruins and some rather elaborate temples which are scattered through the jungle. Some of these were encountered in the course of the survey.

The planned program (Figure 2) consisted of a net of north-south and east-west lines spaced approximately 5 km apart with gravity stations at about one half km interval along the lines. After the program was well advanced, fill-in lines at closer spacing (not shown) were observed in areas where the primary grid developed features of interest.

A primary camp was established at Carmelita (Figure 3) because of the village and airstrip there. The camp, at the edge of the airstrip, had five buildings, including a dining room-kitchen, office, two dormitories and a warehouse. As mentioned above, the airstrip is not servicable in wet weather which presented a problem during the rainy season and made it necessary to keep a large stock of food and supplies in the warehouse at all times.

The logistics of the operation were heavily dependent on air transport, using commercial DC-3s for primary transport, a Grumman Goose amphibian for intercamp transport and helicopters for field transport. Routine supplies were carried

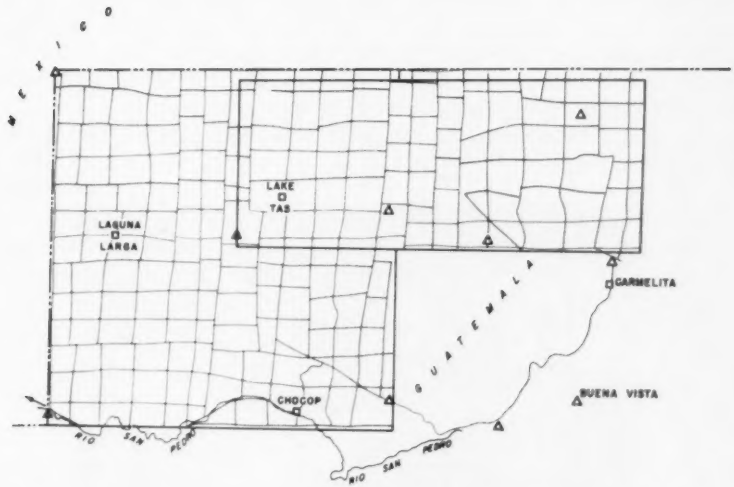


FIG. 2. Concession area, showing gravity program, principal camps: triangles show locations of horizontal control points from Shoran survey.

FIG. 3. Carmelita, with airstrip, showing location of base camp.

from Guatemala City by chartered DC-3, as scheduled flights were not at all adequate. On the average, there were about two DC-3 plane charters per week, one for food and supplies and one for gasoline for the helicopters and amphibian. During the rainy season, a crew of ten laborers was engaged full time filling in tracks to keep the strip in use. Direct radio contact (Figure 4) was maintained from Carmelita to the office in Guatemala City, and also between Carmelita and the field camps.

FIG. 4. Radio equipment for communication from Carmelita camp to Guatemala City office and to base camps.

Because of the nearly complete lack of roads or trails, almost the entire survey was made on lines or brechas cut out through heavy jungle. The only exceptions are the line from Carmelita south and west along the previously mentioned tractor trail and a line along Rio San Pedro (Figure 2). The brecha cutting was done by native laborers, and their number was many times greater than the number required for the gravity operation itself.

While the work was near the Carmelita camp, the helicopters operated directly from the camp to the heliports to the north, northwest and west. Later, as the work extended farther west, the amphibian was used for transport from

Carmelita to base camps, and the helicopters operated from these base camps to the heliports in the jungle.

The helicopters used in this operation were Bell D and G models, capable of carrying two passengers or a cargo load of 325 lb. The range of the D model is one hour and thirty minutes (average speed 30 km/hr) and the G model is two hours and thirty minutes, the G model having larger gas capacity.

Average flight was about 25 km but due to the extensive area worked there were emergency flights of 100 km.

The number of helicopters used were two operational and one standby. The helicopter crew in camp consisted of one pilot, one mechanic and one mechanic trainee (Guatemalan) for each operational helicopter. The helicopter crews worked the same schedule as the gravity crews, i.e., 21 days in camp and seven days rest leave, and therefore had one relief crew. Total personnel with manager was seven Americans and three Guatemalans. During the first four months of operation, the helicopters were used chiefly to transport gravity crews from the base camp, at Carmelita, to work and return daily. Then fly camps were established, and cargo was added to the chores of the helicopters. A repair shop was set up at Carmelita, and major overhauls were conducted there with the exception of magna-flux, which was done in Guatemala City.

## FIELD OPERATIONS

In the beginning of the work, the surveyors and meter operators worked from the Carmelita base camp until they were some 30 km out, and then they were put in mobile camps.

The brecha cutting was done by native crews, furnished by local labor contractors. During 1957, the cutting crews were moved by mule, but in 1958 they were moved by helicopter because of many swamps and lakes in the area and the long distance to travel. The maximum number of local laborers employed was 290 during the early period when a considerable staff was engaged in building camps. When operations had settled to routine, the average number of men working was about 200.

Beginning from Carmelita, trails or brechas were cut along the planned lines of the gravity grid to the north and northwest. Heliports (Figure 5) were cut out at the principal intersections of the network, and men and supplies were carried to them. Heliports were about 40 m wide at the landing end, 20 m wide at the other end, and about 150 m long. The cutting of brush, and often large trees, usually required about two days for an eight-man crew. The relatively large size of the heliports was required because the forest contains trees up to 120 ft high.

After the eastern part of the concession was covered from Carmelita, base camps were established, in order, at Chocop on Rio San Juan, at Lake Tas and at Laguna Largo (locations are shown by Figure 2). These locations, on the water

FIG. 5. Heliport, with helicopter on ground; surrounding jungle trees are up to 120 ft high.

(Figure 6, Figure 7) were selected to avoid construction of airstrips in the jungle and were serviced by the amphibian aircraft (Figure 8), which could operate from the Carmelita airstrip to the river or lakes.

In approximately 60 percent of the area worked, it was necessary to equip the cutting and survey crews with canoes or small boats in order to travel the brechas. In the numerous swamps, there was never enough water to use outboard motors and the boats were poled through the swamps. Most of these swamp areas are quite small, only one half to one km across, but the muck and mud was too deep to wade and difficult to survey. There were three relatively small areas that were open marsh, all in the southern part of the survey and just north of Rio San Pedro. In this small area the helicopters were used to survey and to transport the gravity meter in the same manner as in a Gulf Coast marsh operation. This was a very small fraction of the total as it involved only some 60 stations and took two days to complete.

FIG. 6. Chocop camp, on Rio San Pedro.

A first concern in any jungle operation is the safety of the men against local hazards, including snakes, animals, insects, etc. In the Peten, there are various poisonous snakes, jaguars, and javelinas (wild hogs). Of these, the javelinas proved the most dangerous. Field men experienced numerous encounters with them, and two men were injured in separate attacks. An American received a severe leg injury when attacked by a group of javelinas. A native received a hand and leg injury from javelinas. It was not unusual to see a group of as many as 50 javelinas. The only escape is to climb a tree, as few men can outrun a hog in the bush. The snakes and jaguars will stay clear of humans if given a chance to move away, and no injuries from them were experienced.

Except for the problems of transportation, the gravity operation itself was carried out in the usual way. Base stations were established at the heliports with the ties being made by helicopter. The average closure error of base loops was approximately .07 mg. Elevations and horizontal control were carried by transit and stadia with vertical and horizontal closures averaging approximately 30 cm and 35 m respectively. Lines between heliport bases were run on foot (Figure 9, Figure 10), or by boat, along the cut brecha to the next heliport. The results

FIG. 7. Lake Tas camp.

FIG. 8. Grumman Goose, used for transport from Carmelita airstrip to base camps.

FIG. 9. Surveyors on brecha.

FIG. 10. Meter operator on brecha.

were worked up and preliminary maps prepared in the Carmelita camp and sent to Guatemala City, where prints were made for transmittal to Houston for final assembly and interpretation.

## PERSONNEL AND WORK SCHEDULES

The American personnel of 11 men included: an agent or accountant in Guatemala City to obtain supplies and keep the usual and special government records; the Party Chief (the junior author) with his assistant and two computers in the Carmelita camp; four surveyors and two meter operators in the field. In the later part of the operation, three meters were used in the field. By that time, several natives had been trained to be quite competent as meter operators and as surveyors. A staff house was rented in Guatemala City which served as an office for the operation and as headquarters for the field men whenever they came into town.

For the American personnel, the work schedule was seven days a week, with each staff member (except the Party Chief) working 21 days in the bush with eight days out which were either in Carmelita or in Guatemala City. The operation was not shut down completely during off-periods as use was made of native assistant surveyors and meter operators to rotate the men in and out of the field.

It took some time to develop the various phases of the operation and to find

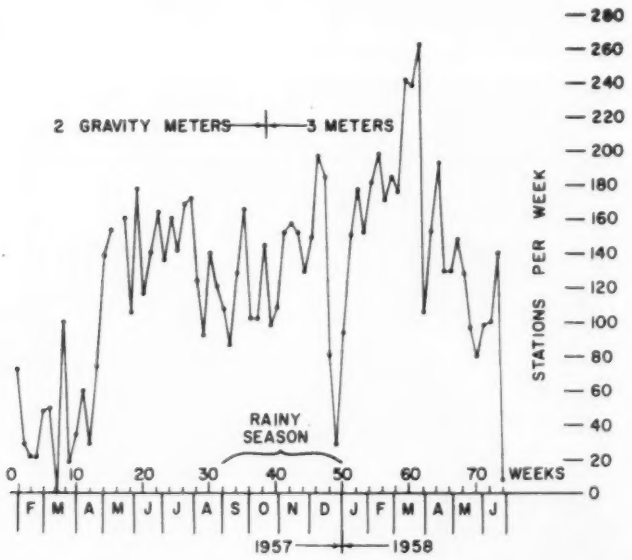


FIG. 11. Curve showing weekly production of completed stations.

and train natives to cut brechas and heliports, establish camps, etc. After the organization was shaken down, production was around 150 to 180 stations per week (Figure 11).

The organization of the field operation as finally developed was approximately as follows:

Seven cutting camps, each under a labor contractor; each such unit consisted of two cutting crews of five men each, two cooks, one or two camp helpers, one or two mule drivers, and seven or eight mules.

Six surveyor camps, each with one American or native surveyor, five native assistants, two helpers, one cook, one camp helper, one mule driver, and eight mules.

Three meter camps, each with one meter operator, one helper, one cook, one camp helper, one mule driver, and six or eight mules.

This required approximately 150 natives in the mobile camps and around 100 mules. It was not necessary to carry food for the mules as they live off the leaves of the Ramon tree.

In the Carmelita camp there were usually about 20 Americans, including the gravity meter and helicopter personnel, and around 30 natives who maintained the camp, loaded and unloaded supplies between aircraft and warehouse, worked on the airstrip, etc.

### STATISTICS OF THE OPERATION

The following table gives over-all and monthly statistics of the operation which extended from February 1957 to June 1958.

| | |
|---|---|
| Total area of concession | 2,100 sq mi (1,350,000 acres) |
| Total production | 9,375 gravity stations |
| Average production rate | 551 stations/month (for 17 months) |
| Best monthly production rate | 944 stations (March 1958, dry season) |
| Total brecha cut | 2,717 km |
| Total number of heliports cut | 233 |

Aerial Operations

| | Helicopters | Amphibian |
|---|---|---|
| Total hours flown | 3,435 (17 months) | 520 (5 months) |
| Monthly Averages | | |
| Flying time | 202 hours | 104 hours |
| Passengers carried | 460 | 301 |
| Cargo carried | 46,668 lb. | 61,373 lb. |
| km flown | 17,636 | 19,985 |

### OTHER OPERATIONS IN THE AREA

The entire Peten Province of northern Guatemala had been covered by an aeromagnetic survey prior to the gravity meter survey. The horizontal control for the aeromagnetic survey was by Shoran (Brundage, 1958). In connection with this survey, a number of horizontal control points on the ground were located

by Shoran controlled aerial photography. Seven of these points are within the area of the gravity survey shown by triangles (Figure 2) and were tied to the horizontal control network. The final mapping of the gravity results was adjusted to the Shoran control points. In this way, in spite of the extreme difficulty of the survey itself, the final mapping is at least as good and probably somewhat better than that obtained in the usual land surveys with occasional triangulation stations for control.

ACKNOWLEDGMENT

The authors are indebted to Texas Petroleum Company, operator, and their associates in the concession area, for permission to publish this paper.

REFERENCE

Brundage, H. T., 1958, Geodetic-magnetic survey aids Guatemala exploration: World Oil, p. 205–209.

GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1035–1053, 10 FIGS

# NOMOGRAMS TO SPEED UP SEISMIC REFRACTION COMPUTATIONS*

TSVI MEIDAV†

## ABSTRACT

Nomographic solutions of a number of equations commonly employed in seismic refraction work are presented. The equations solved are: 1. Depth to a second layer, by means of the critical distance formula. 2. The critical angle and offset distance formulas. 3. True velocity of bedrock from the apparent up- and down-dip velocities. 4. Depth to a second layer by means of the intercept-time formula. This last solution is also applied to (a) finding the throw of a fault and (b) depth to an irregular second layer at each seismometer beyond the critical distance. Geometry of each of the nomograms is explained. Procedure for using each of the nomograms is described.

## INTRODUCTION

A number of nomograms were constructed to solve some equations commonly employed in seismic refraction determinations of depth to a velocity discontinuity. The purpose of these nomograms is to shorten the time required for the solution of equations which are used repetitively. The convenience of being able to avoid the tedium of such calculations is obvious. The accuracy of most of the nomograms is usually in the two-significant-figures range, with the third figure interpolated. This accuracy is as good or better than the average data accuracy available.

## CONSTRUCTION OF THE NOMOGRAMS

A nomogram is a graphical representation of a mathematical relationship. Nomograms are employed to solve mathematical expressions by some simple geometric operations, such as drawing a straight line between scales of the independent variables, the intersection of which with another scale determines the value of the dependent variable. The scales of a nomogram are functional. A *functional scale* is one in which the distances from one graduation to another are proportional to the values of the *variable function* $F_i(x_i)$, but the numerical values of the graduations are those of the *variable* $x_i$. Logarithmic graph paper is a typical example of a nomographic plot.

In constructing a scale to represent the values of a function between given limits, it is necessary to multiply each value of the function by some proportionality factor, so that the scale will stay within a desired length. Such a proportionality factor is called the *scale modulus*. The *scale equation* is the product of the variable function $F_i(x_i)$ and the scale modulus $m_i$, as given in equation 1.

$$S_i = m_i F_i(x_i), \tag{1}$$

where $S_i$ is the scale distance to the value $x$ on the $i$th scale.

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Discussion of nomogram construction is available in many standard texts (e.g.: Hoelscher, Arnold and Pierce, 1952; Giet, 1954; Levens, 1959). These texts include solutions of standard linear and non-linear equations. A common procedure employed by nomogram designers to save time and energy is to convert the equation on hand into any of the standard forms handled in textbooks, and use the readily available solution of the textbook. The derivation of solutions of the seismic refraction equations treated in this paper is given below for the sake of completeness, although the understanding of the mechanics of nomogram construction is in no way a prerequisite for using them.

## THE CRITICAL DISTANCE NOMOGRAM

The critical distance nomogram (Figure 1) solves the equation

$$Z = \frac{x_c}{2}\sqrt{\frac{V_1 - V_0}{V_1 + V_0}}, \tag{2}$$

where

$x_c$ = the critical distance
$V_0$, $V_1$ = wave velocities above and below the discontinuity, respectively.
$Z$ = depth to the second layer.

*Derivation of the critical distance nomogram*

Let

$$\left.\begin{aligned} S_{V_0} &= m_{V_0} f_1(V_0) \\ S_{V_1} &= m_{V_1} f_2(V_1) \\ S_{x_c} &= m_{x_c} f_3(X_c) \\ S_Z &= m_Z f_4(Z) \end{aligned}\right\} \tag{3}$$

The meaning of the nomenclature for the following geometric derivation is indicated in Figure 2.

By construction, let

$$\overline{EJ} \perp \overline{CE}$$

$$\overline{FB} \perp \overline{BG}$$

$$\angle ELB = \angle BKJ = 45°$$

$$\overline{DC} \parallel \overline{GF}$$

$$\overline{OA} \parallel \overline{GH} \parallel \overline{JE}$$

$$\overline{OG} \parallel \overline{EC}.$$

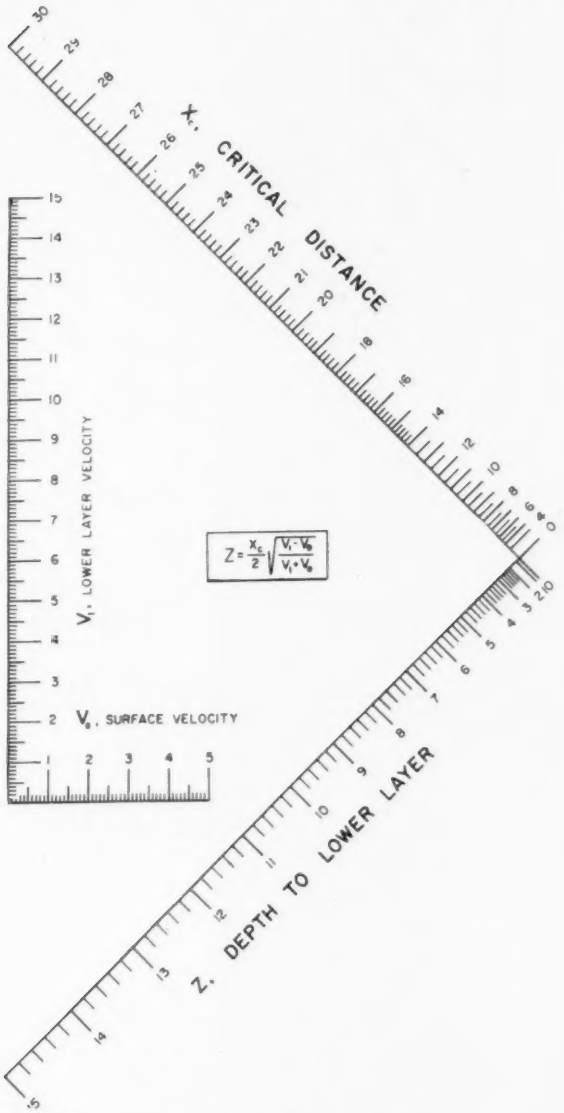


FIG. 1. The Critical Distance Nomogram. To find depth to the discontinuity, connect $V_1$ with $V_0$. Pass another line through $X_c$ parallel to the line $V_0V_1$. The value of the intersection of the second line with the $Z$ scale is the depth to the discontinuity.

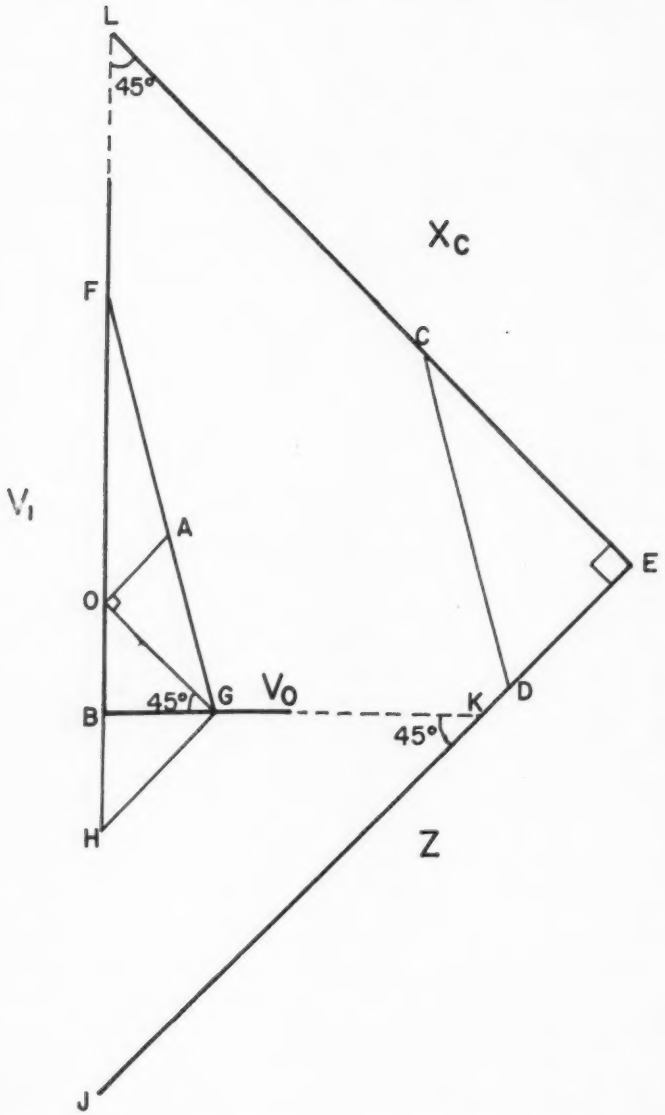


FIG. 2. Geometric setup for the derivation of the Critical Distance Nomogram.

Then,

$$\frac{\overline{FO}}{\overline{FB} + \overline{BH}} = \frac{\overline{OA}}{\overline{GH}}$$

or,

$$\frac{V_1 - V_0}{V_1 + V_0} = \frac{\overline{OA}}{\overline{GH}} .$$

However, triangles AOG and CDE are similar. Therefore,

$$\frac{\overline{AO}}{\overline{GO}} = \frac{f_4(Z)}{f_3(x_c)} .$$

Also,

$$\overline{GH} = \overline{GO}$$

hence,

$$\frac{V_1 - V_0}{V_1 + V_0} = \frac{f_4(Z)}{f_3(x_c)} .$$

Let

$$f_4(Z) = Z^2$$

$$f_3(x_c) = \frac{x_c^2}{4} .$$

Then,

$$m_Z f_4(Z) = m_{x_c} f_3(x_c) \frac{m_{V_1} f_2(V_1) - m_{V_0} f_1(V_0)}{m_{V_1} f_2(V_1) + m_{V_0} f_1(V_0)} . \tag{4}$$

Equation 4 is a general solution for a class of equations of the type of equation 2. Equation 4 may be simplified considerably by letting $m_{V_0} = m_{V_1}$, and $m_{X_c} = m_Z$. After taking the square root of both sides of equation 4, the nomogram equation reduces to

$$m_1 Z = \frac{m_1 x_c}{2} \sqrt{\frac{m_2 V_1 - m_2 V_0}{m_2 V_1 + m_2 V_0}} , \tag{5}$$

where $m_1$ and $m_2$ are arbitrary scale moduli. Their magnitude is determined by the range of variables and the desired physical size of the nomogram. The scales are constructed of two independent pairs: the $V_0$, $V_1$ pair, and the $x_c$, $Z$ pair. The scales of each pair must be orthogonal to each other and must have an angle of 45° with scales of the opposite pair, as shown in Figure 2.

*Accuracy of the critical distance formula*

The critical distance formula is considered by many practicing geophysicists to be the most reliable of the various depth formulas available, whenever a distinct change of slope is present on the time-distance curve. The above assertion may be verified by an investigation of the effect of errors involved in determining any of the independent variables of equation 2.

Let $M$ represent the radical in equation 2. Assume that for a given value of $M$, an error of magnitude $\Delta x_c$ was committed. Let $M$ be normalized to equal unity in some arbitrary units. Then, the total error $\Delta Z$ in determining depth correctly is given by

$$\Delta Z = \tfrac{1}{2}\Delta x_c.$$

Thus, the error in depth determination is *one half* the error involved in determining the critical distance.

The effect of an error in determining $V_0$ or $V_1$ correctly may be seen by rewriting equation 2 as

$$Z = \frac{x_c}{2}\sqrt{\frac{1-\dfrac{V_0}{V_1}}{1+\dfrac{V_0}{V_1}}} = \frac{x_c}{2}\sqrt{\frac{1-R}{1+R}} = \frac{x_c}{2}M. \tag{6}$$

Equation 6 indicates that it is the *ratio* $V_0$ to $V_1$ which determines the magnitude of the radical, not the individual values of $V_0$ and $V_1$. The effect of errors in correctly determining the ratio $R = V_0/V_1$ on the accuracy, or error, in evaluating the radical in equation 6, can be found as follows:
Let

$R = R_{\text{approx}} + \Delta R$
$R =$ correct value of $V_0/V_1$

where

$\Delta R =$ the error.

Then, $\Delta R/R$ is the relative error in $R$, and $\Delta R/M$ is the relative error in $M$.

Figure 3 shows that as the ratio $R$ decreases, the relative error of $M$ decreases for given values of $\Delta R$. For example, when $V_0/V_1 \leq 1/5$, the change in the value of $M$, the radical in equation 2, is less than 25 percent for an error $\Delta R$ of 100%.

*Use of the critical distance nomogram*

The critical distance nomogram is of the proportional chart type. The given scales may be used in any units of measurement such as feet, yards, meters or any arbitrary units.

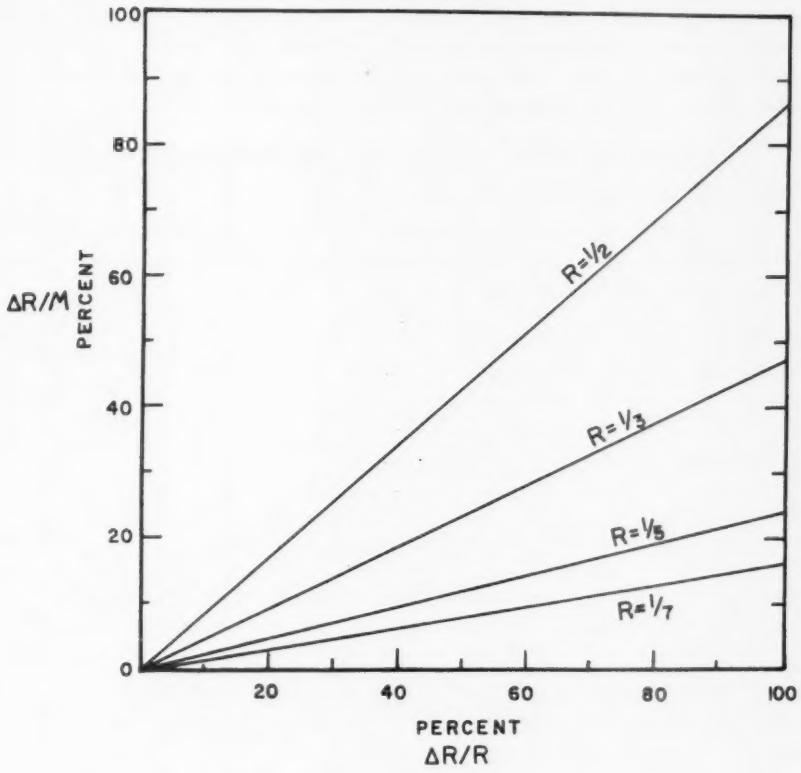


FIG. 3. Relative error in percent for values of $\Delta R$. Note that as $R$ decreases so does the relative error in $M$.

For determination of depth, align a triangle to intersect the values of $V_0$ and $V_1$. The order of magnitude of $V_0$ and $V_1$ must be consistent. It is permissible to double or halve the values of both $V_0$ and $V_1$ if any scale is too short on either end, without changing the final result. Set a straight edge at the base of the triangle and slide the triangle parallel to the slope of the $\overline{V_0V_1}$ line until the triangle edge which is parallel to the $\overline{V_0V_1}$ line intersects the value of the critical distance $x_c$ of the given case. Opposite the value of $x_c$, along the triangle edge, one reads the value of $Z$, the depth to the second layer. If the value of $x_c$ is located very close to the origin, and hence cannot be read accurately enough, or if it is beyond the last value of the scale, it is permissible to double or halve the value for convenience and accuracy, but then the final answer must be halved or doubled, respectively (note the order!). Instead of using a triangle and a

straight edge, it might be easier at times to use any type of rectangular graph paper, rotated to intersect with one edge the values of $V_0$ and $V_1$. Follow the graph line which intersects the appropriate $x_c$ value to its intersection with the $Z$ scale, which will be the corresponding depth value.

## THE CRITICAL ANGLE AND OFFSET DISTANCE NOMOGRAM

### *Construction of the nomogram*

An $N$ type (sometimes referred to as the $Z$ type) was constructed to solve the critical angle and offset distance equations. The $N$ type nomogram solves multiplication problems such as

$$f(u)g(v) = h(w),$$

or division problems of the type

$$g(v) = h(w)/f(u).$$

Let the scale equations of $u$ and $v$ be given by

$$S_u = m_u f(u)$$
$$S_w = m_w h(w).$$

Referring to Figure 4, the diagonal scale $g(v)$ connects the zero values of the functions $f(u)$ and $h(w)$. The arrows indicate the direction of ascending values of the function. The diagonal scale ranges from zero at its intersection with the $W$ scale, to infinity, at its intersection with the $U$ scale.

From the geometry of Figure 4, it is seen that

$$\frac{\overline{AB}}{\overline{AC}} = \frac{\overline{DE}}{\overline{AE} - \overline{AC}}. \tag{7}$$

Let

$$\left.\begin{aligned} \overline{AB} &= S_w = m_w h(w) \\ \overline{ED} &= S_u = m_u f(u) \\ \overline{AC} &= S_V \end{aligned}\right\}. \tag{8}$$

From equations 7 and 8 we have

$$\frac{\overline{AB}}{\overline{DE}} = \frac{\overline{OC}}{\overline{OE} - \overline{OC}} \tag{9}$$

or

$$\frac{m_w h(w)}{m_u f(u)} = \frac{S_v}{\overline{AE} - S_v}. \tag{10}$$

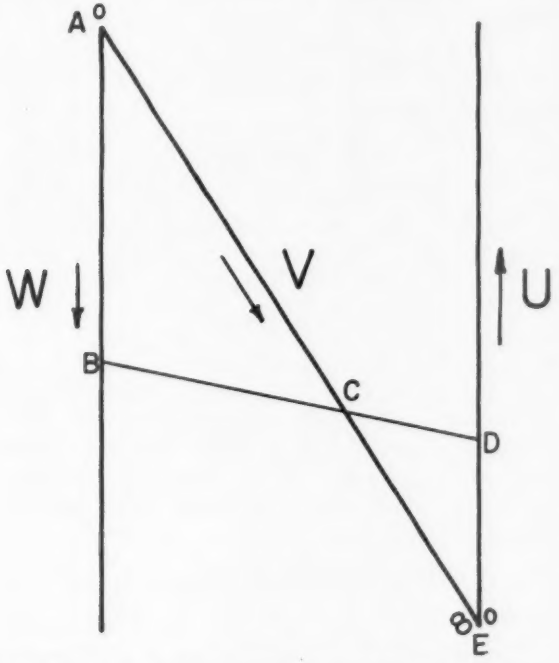


FIG. 4. Skeleton of the Critical Angle and Offset Distance Nomogram. The arrows indicate directions of increasing values of the functions.

Solving for $S_v$, the scale equation of $V$, we have

$$S_v = \frac{\overline{AE}g(v)}{g(v) + \dfrac{m_u}{m_w}}. \tag{11}$$

Equation 11 can be simplified by letting $m_u = m_w$ whenever possible. Then,

$$S_v = \overline{AE}\,\frac{g(v)}{g(v)+1}. \tag{12}$$

Thus, by selecting values for the moduli $m_u$ and $m_w$, which are convenient in terms of the length of these scales, it is possible to determine the distance to each of the graduations of the $V$ scale. This is done by selecting values of $v$ and substituting these in equation 11 or 12. For a simple graphical method of graduating the diagonal scale, the reader is referred to Hoelscher et al (p. 78).

*Uses of the nomogram*

The critical angle and offset distance nomogram (Figure 5) may be used to solve two basic equations. First, it yields the value of $i_c$, the critical angle of incidence, from the equation

$$i_c = \arcsin V_0/V_1. \tag{13}$$

Using the value of $i_c$ from equation 13, it is possible to determine the offset distance $X$, i.e., the distance by which the depth determination should be moved towards the shotpoint, due to the fact that the upcoming ray is not vertical, but is inclined at angle $i_c$. The offset distance is given by the equation

$$X = Z \tan i. \tag{14}$$

The offset distance correction is generally negligible when $V_1$ is much greater than $V_0$, but assumes increasing importance as $V_1$ decreases relative to $V_0$.

To obtain $i_c$, pass a straight line through $V_1$ and $V_0$, and read the intersection of that line with the $i_c$ scale. To find the offset distance, transfer the value obtained from the above step to the $i$ scale. Connect a line through $Z$ and $i$. The intersection of the line with the $X$ scale is the value of the offset distance, and is in the same units used for $Z$.

## THE TRUE VELOCITY NOMOGRAM

*Construction of the nomogram*

The alignment chart employed to solve the equation of the true wave velocity of a slightly dipping layer is of the concurrent type. The concurrent type chart is particularly useful in solving all equations of the type

$$\frac{1}{f(u)} + \frac{1}{g(v)} = \frac{1}{h(w)}, \tag{14}$$

or all equations reducible to that form.

Referring to the geometry of Figure 6, the basic principle of the concurrent type nomogram is as follows:

$$\text{Area } OAC = \text{Area } OAB + \text{Area } OBC.$$

Therefore,

$$\tfrac{1}{2}ac \sin \psi = \tfrac{1}{2}ab \sin \theta + \tfrac{1}{2}bc \sin \phi. \tag{15}$$

Dividing equation 15 by $\frac{1}{2}abc$, we get

$$\frac{\sin \psi}{b} = \frac{\sin \theta}{c} + \frac{\sin \phi}{a}. \tag{16}$$

The lengths $a$, $b$, $c$, may be given as specific values of the corresponding scale equations

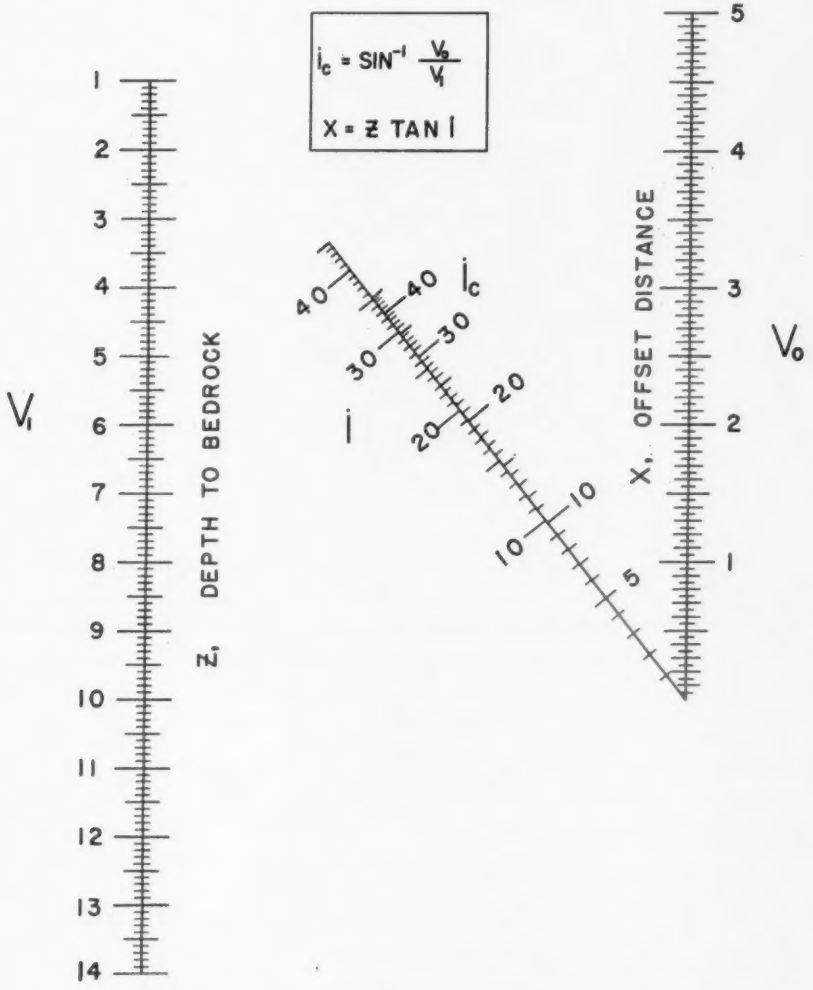


FIG. 5. The Critical Angle and Offset Distance Nomogram. Connect $V_0$ with $V_1$, and read $i_c$, the critical angle. Transfer $i_c$ value to $i$ scale. Pass a line through $i$ and $Z$ and read off $Z$, the offset distance.

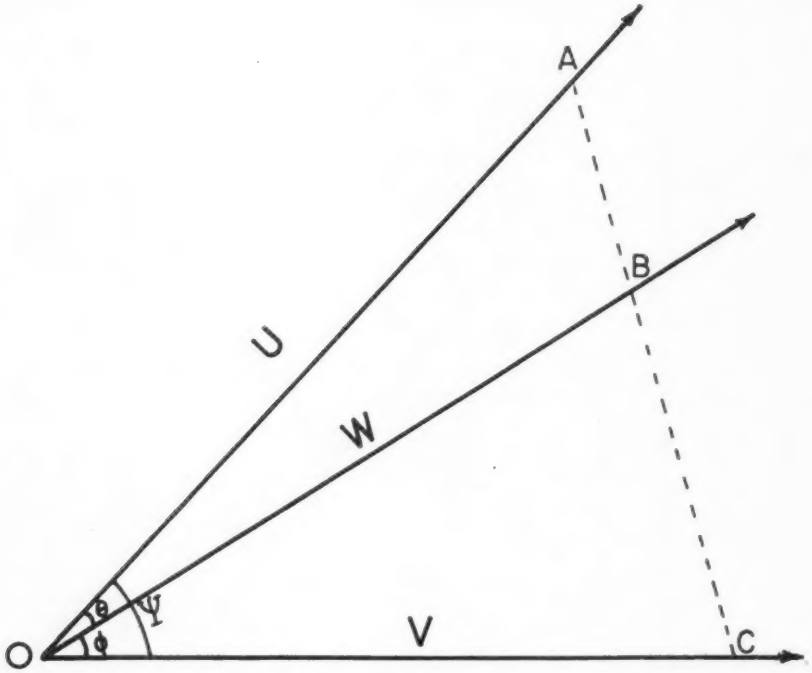


FIG. 6. Skeleton of the True Velocity Nomogram.

$$\left.\begin{aligned} a &= m_u f(u) \\ c &= m_v g(v) \\ b &= m_w h(w) \end{aligned}\right\}. \tag{17}$$

From equations 16 and 17, we obtain

$$\frac{\sin \psi}{m_w h(w)} = \frac{\sin \theta}{m_u f(u)} + \frac{\sin \phi}{m_v g(v)}. \tag{18}$$

However, if the nomogram is so designed that

$$\frac{\sin \psi}{m_w} = \frac{\sin \theta}{m_u} = \frac{\sin \phi}{m_v} \tag{19}$$

then, equation 18 reduces to equation 14

$$\frac{1}{h(w)} = \frac{1}{f(u)} + \frac{1}{g(v)}. \tag{14}$$

The position of the $W$ scale is found by solving the simultaneous equations for $\theta$ and $\phi$.

$$\left.\begin{aligned} \theta + \phi &= \psi \\ \frac{\sin\theta}{m_u} &= \frac{\sin\phi}{m_v} \end{aligned}\right\}. \tag{20}$$

The modulus of the $W$ scale is given by

$$m_w = m_u \frac{\sin\psi}{\sin\theta} \tag{21}$$

or by

$$m_w = m_v \frac{\sin\psi}{\sin\phi}. \tag{22}$$

Equations 21 and 22 can be further simplified by choosing $\psi$ to be 90° or 120°.

If $\psi = 90°$, then

$$m_w = \sqrt{m_u^2 + m_v^2}.$$

To reduce the labor in constructing a concurrent type nomogram it is often desired to have all three moduli equal to each other ($m_u = m_v = m_w$). Substituting this condition in equation 19, we have

$$\sin\psi = \sin\theta = \sin\phi, \tag{23}$$

but we also had

$$\psi = \theta + \phi. \tag{24}$$

The only angle $\psi$, for which equations 23 and 24 hold simultaneously is 120°. Hence, $\theta = \phi = 60°$. This special case is employed in the true velocity nomogram, Figure 7.

The true velocity of a dipping bed is given by

$$V_1 = \frac{2\cos\theta}{\frac{1}{V_u} + \frac{1}{V_d}} \cong \frac{2}{\frac{1}{V_u} + \frac{1}{V_d}}, \tag{25}$$

where

$\theta$ = dip angle
$V_u$ = updip velocity
$V_d$ = downdip velocity.

The last expression in equation 25 is an approximation which is sufficiently

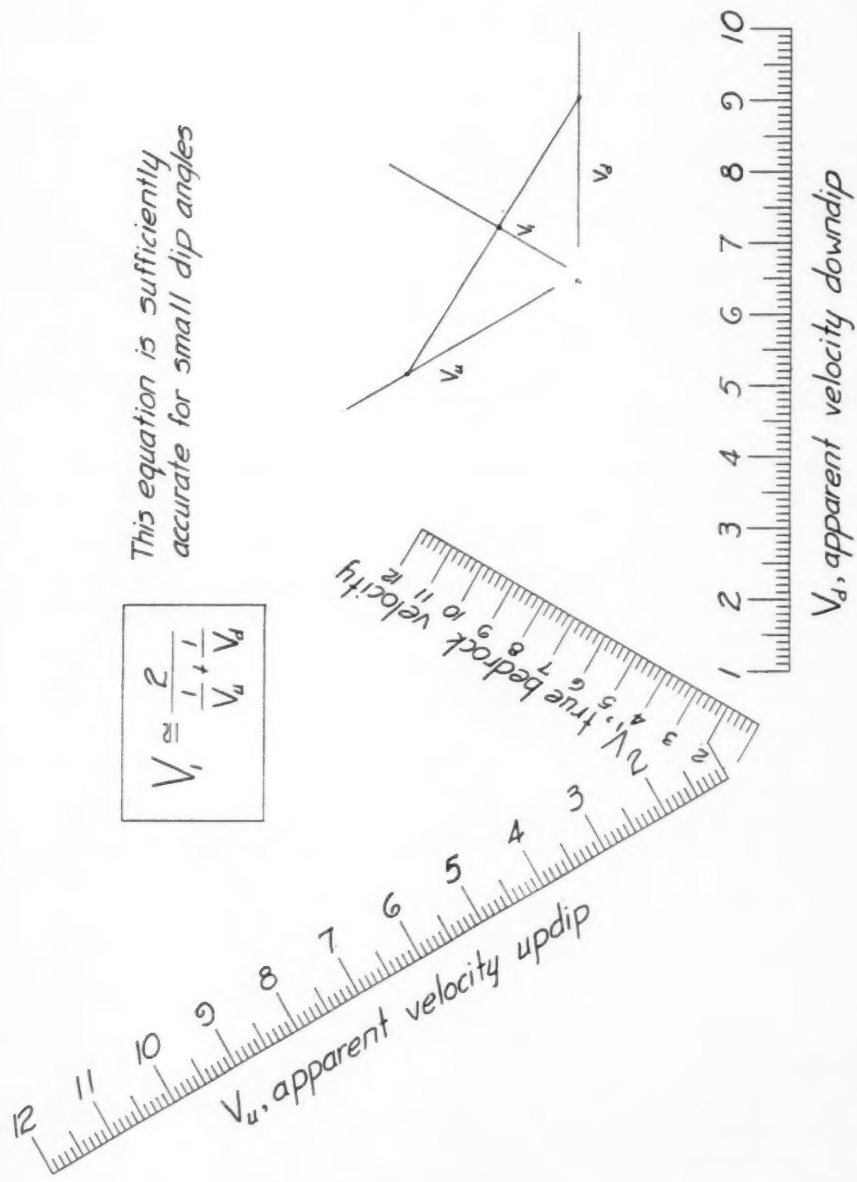
$V_1 \cong \frac{2}{\frac{1}{V_u} + \frac{1}{V_d}}$
This equation is sufficiently accurate for small dip angles
$V_u$
$V_d$
$V_1$, true bedrock velocity
$V_u$, apparent velocity updip
$V_d$, apparent velocity downdip

FIG. 7. The True Velocity Nomogram. Connect $V_u$ with $V_d$ and read the intersection of the line with $V_1$, the true velocity.

accurate for small angles of dip. By algebraic manipulation equation 25 can be rewritten as

$$\frac{1}{V_1} \cong \frac{1}{2V_u} + \frac{1}{2V_d} . \tag{26}$$

Equation 26 is of the exact form of equation 14. Note that although the scale moduli are all equal in this chart, the *functional* moduli of $V_u$ and $V_d$ are twice as large as the modulus $V_1$ (Figure 7). The *functional modulus* is defined as the scale modulus times any numerical constant that may be factored out of the function considered.

*Use of the true dip nomogram*

As stated above, equation 26 is sufficiently accurate for small angles of dip only. In instances where this condition holds, the inherent errors of the seismic method may be greater than the error introduced in the nomogram by the above approximation. To obtain the true velocity $V_1$, which is the value to be used in all depth computations, simply connect $V_u$ with $V_d$ and read the intersection of $V_1$, the value of the true velocity.

## THE INTERCEPT-TIME NOMOGRAM

*Construction of the nomogram*

The intercept-time nomogram (Figure 8) was constructed by employing both the concurrent type and the $N$ type nomograms in the solution of the equation

$$Z = f(t)A, \tag{27}$$

where

$$A = \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}} . \tag{28}$$

Equation 28 can be rewritten as

$$\frac{1}{A^2} = \frac{1}{V_0^2} - \frac{1}{V_1^2} ,$$

which is in the form of the standard concurrent type nomogram. The intercept-time nomogram was constructed in the same manner as the true velocity nomogram, with the exception that in this instance, the angle between the two outer scales was selected to be 90° instead of 120° (Figure 8). The position of the $V_0$ scale was determined from equation 20.

Having solved for $A^2$ above, it is possible to determine the depth to a velocity discontinuity from the intercept time formula, written in the form

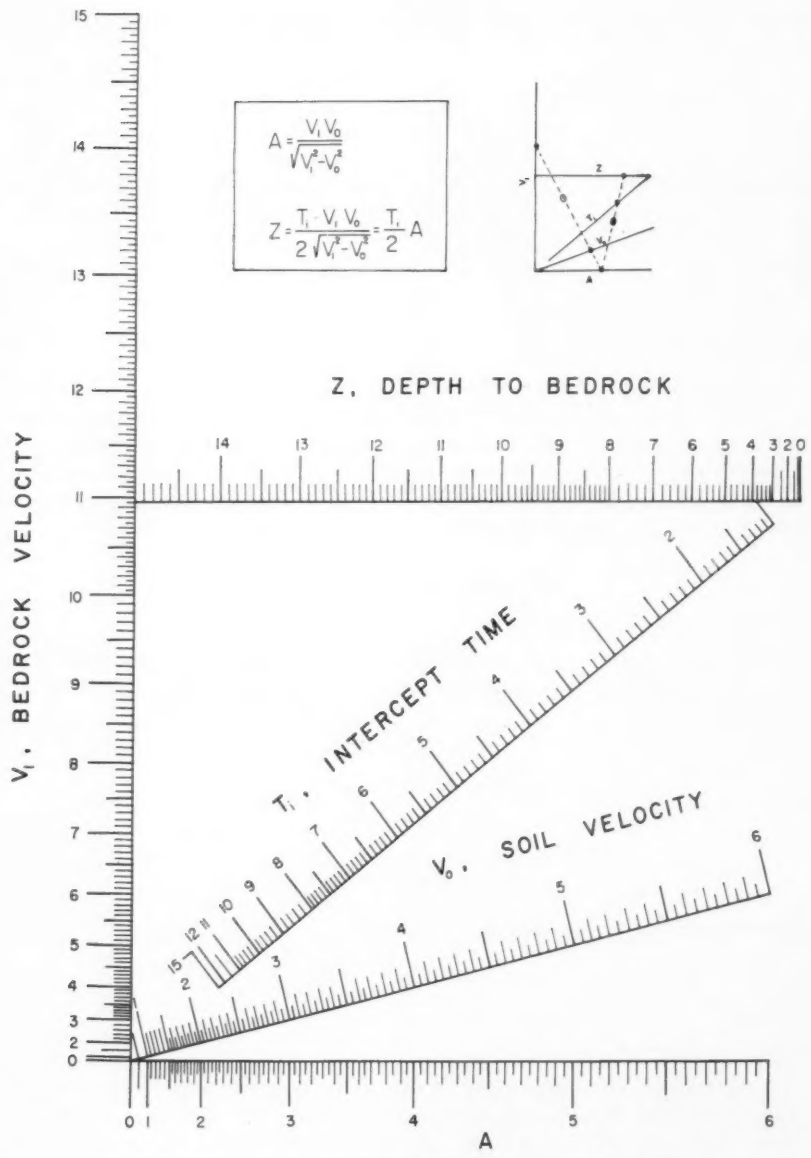
$A = \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}}$
$Z = \frac{T_i \cdot V_1 V_0}{2\sqrt{V_1^2 - V_0^2}} = \frac{T_i}{2} A$
Z, DEPTH TO BEDROCK
$V_1$, BEDROCK VELOCITY
$T_i$, INTERCEPT TIME
$V_0$, SOIL VELOCITY
A

FIG. 8. The Intercept-Time Nomogram. Pass a line through $V_0$, $V_1$ to $A$. Using the specific value of $A$ from the preceding step, pass a second line from $A$ through $t_i$ to $Z$, the depth (see inset for example).

$$Z^2 = \left(\frac{t_i}{2}\right)^2 A^2, \tag{29}$$

where $t_i$ is the intercept-time.

Equation 29 may be recognized as being adaptable to the $N$ type chart, and is solved in the same manner as the critical angle nomogram.

*Uses of the nomogram*

The intercept-time nomogram can be used to solve seismic refraction equations which have in common the factor $A$ of equation 28.

One of the most important of these equations is the intercept-time equation, given by

$$Z = \frac{t_i}{2} \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}}. \tag{30}$$

A second equation containing the factor $A$ is that for calculating the throw of a normal fault, height of a pinnacle or a buried scarp. This equation has the form

$$\Delta Z = \Delta t \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}} = \Delta t \cdot A, \tag{31}$$

where

$\Delta Z$ = the vertical displacement of the fault
$\Delta t$ = the step-up or step-down time, defined by Figure 9.

A third equation which contains the factor $A$ is the approximation for the depth associated with each seismometer beyond the critical distance to a slightly dipping or irregular discontinuity. For small angles of dip, the total travel time $T_j$ may be approximated by

$$T_j = \frac{X_j}{V_1} + (Z_1 + Z_j)\left(\frac{\cos i}{V_0}\right), \tag{32}$$

where

$X_j$ = distance to the $j$th seismometer
$Z_1$ = depth to the discontinuity near the shotpoint
$Z_j$ = depth to the discontinuity near the $j$th seismometer
$i$ = critical angle of incidence.

Solving equation 32 for $Z_j$, the unknown depth, and simplifying

$$Z_j \cong \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}}\left(T_j - \frac{X_j}{V_1}\right) - Z_1 = A\left(T_j - \frac{X_j}{V_1}\right) - Z_1. \tag{33}$$

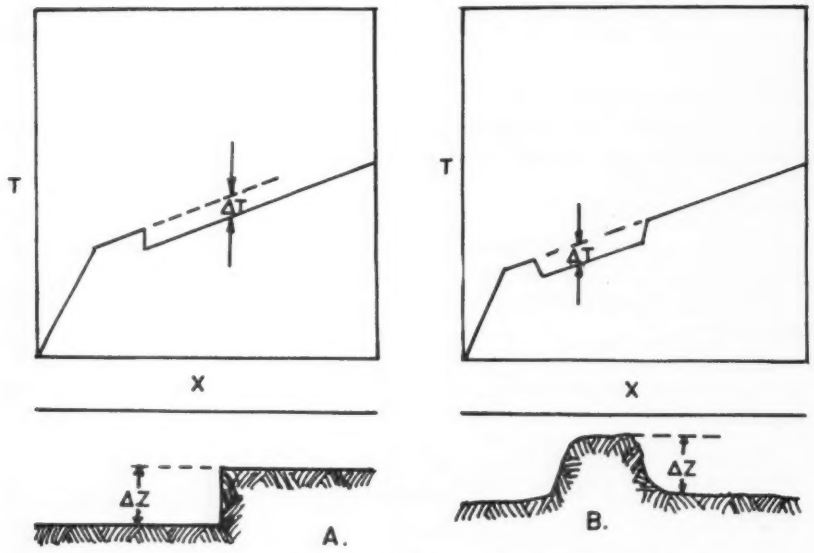


FIG. 9. Time-distance curve for (A) a fault with a finite displacement or a buried scarp, and (B) a buried pinnacle.

Thus, if one depth, $Z_1$, is known, the depth to the discontinuity $Z_j$ may be approximated by repeatedly solving equation 33 for each value of $X_j$, $T_j$.

The value of $A$, the common factor in equations 30–33, may be found from the intercept-time nomogram (Figure 8), by passing a straight line from $V_1$ through $V_0$, and reading the value of its intersection on the $A$ scale.

To solve equation 30, pass a line from the value of $A$, determined from the

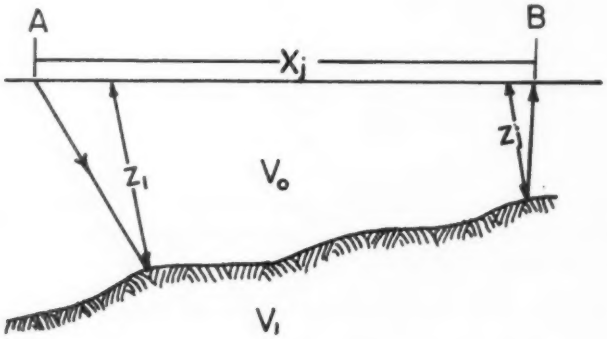


FIG. 10. Ray trajectory when bedrock surface is irregular.

above step, through the $t_i$ value on the $t_i$ scale, and read the value at its intersection on the $Z$ scale. That value is the depth to the discontinuity. Again, $V_1$ and $V_0$ may be taken in any units. For example, if the values of $V_1$, $V_0$ are taken in kilofeet/sec and $t_i$, the intercept time, in millisec, $Z$ will come out in ft. However, $t_i$ may be read in tens or tenths of millisec and $Z$ will come out in tens or tenths of ft accordingly.

To solve equation 31, follow the same procedure as for the solution of equation 30 with one exception: the value of $Z$ obtained from the nomogram must be doubled to obtain the correct value of $\Delta Z$, owing to the difference in equations.

*Reliability of the intercept-time equation*

The intercept-time equation is considered to be less accurate than the critical distance formula for instances where the value of $V_0$ is not known with high precision. When $V_1 \gg V_0$, it is seen that

$$\frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}} \cong V_0.$$

Thus, the error in determining depth from equation 28, when $V_1 \gg V_0$, varies *directly* with $V_0$, as compared with a much smaller error resulting from the use of a wrong $V_0$ value in equation 2. Furthermore, it is often more difficult to determine the correct slope of segments of the time-distance curve, and hence the resultant intercept times, than to determine the critical distances. Of course, there are undoubtedly cases where the reverse of the last statement is true, in which case the intercept-time formula is the more useful one.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1054–1076, 14 FIGS.

# USES OF THE GAMMA-RAY SPECTROMETER IN MINERAL EXPLORATION*

JOHN L. MERO†

## ABSTRACT

Gamma-ray spectroscopy offers a rapid and reliable radiometric method of analysis of uranium and/or thorium ores. Methods of ore analysis are described and experimental results are presented. The uranium-thorium ratios of rocks, which are important in strata recognition and correlation studies, can be determined directly by gamma-ray spectroscopy without the necessity of making individual uranium or thorium assays. Analysis of potash ores is facilitated with a gamma-ray spectrometer. Erratic behavior of gamma-ray well logs can often be resolved by studying the gamma-ray spectra of these logs. Neutron-activation, followed by gamma-ray spectral analysis, of common earth materials offers a method of borehole rock analysis for elements such as calcium, hydrogen, chlorine, sulphur and magnesium. Data in studies employing radioactive tracers can often be enhanced through use of a gamma-ray spectrometer. Other present and potential applications of the gamma-ray spectrometer in mineral exploration are also discussed.

## INTRODUCTION

Gamma-ray spectrometers have been used for many years by the petroleum industry. In the neutron logging of a well, a Geiger tube, shielded against the low-energy radiation emitted by naturally-occurring radioactive elements, but intercepting the high-energy gamma ray of the excited hydrogen atom serves as a crude, but effective, gamma-ray spectrometer (Pontecorvo, 1941).

More sophisticated spectrometers, however, generally employ an electronic means of differentiating between the energies of various intercepted gamma rays. A common arrangement is a scintillation detector which converts an intercepted gamma ray to an electric impulse, the voltage of which is proportional to the energy of the absorbed gamma ray. This impulse is amplified and passed through an electronic gating circuit which allows only pulses of a specific voltage to actuate a scaler. Gamma rays emitted by radioactive nuclides are of characteristic energies and the intensity of the gamma radiation emitted by a specific nuclide is proportional to the quantity of that nuclide present in a sample.

Because of the facility and low-cost-per-unit assay when making large numbers of analyses for gamma-emitting nuclides, gamma-ray spectrometers are beginning to find application in the analysis of ores and other earth materials for uranium and thorium. Since the early 1950's a number of experiments have been performed using a gamma-ray spectrometer to analyze the gamma radiation emitted by earth materials when bombarded by neutrons. The end view of these research programs is the application of the gamma-ray spectrometer to isotopic analysis of the wall rock constituents in boreholes.

The method used to obtain the gamma-ray spectrum graphs used to illus-

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trate this report may be of some interest. Instead of lowering the bias on a pulse gating circuit as is the usual method of sweeping the gamma-ray spectrum with a pulse height analyzer, the bias on the gating circuit was held constant. While holding the pulse gate at a fixed level, the voltage on the photomultiplier in the scintillation detector was linearly increased with respect to time. The output pulse from the gate was fed to a linearly-moving graphic recorder. Although this method results in a logarithmic spacing of the photon energy on the graph, good resolution throughout the whole gamma spectrum is obtained. The results of this method of gamma-ray spectral analysis on a mixture of radioactive nuclides are shown in Figure 1. A plot of the energy of a photon peak vs the voltage at which the peak appears in the preset spectrometer window will yield a straight line graph on semi-log paper. Such a graph facilitates the determination of the energies of photon peaks in any spectral analysis work.

The individual samples of ore used in gathering data for this paper weighed 20.0 gm and were packed in aluminum cups 5.0 cm in diameter. During counting periods, the ore samples were placed about 2.0 cm from the face of a $1\frac{1}{2}$-inch by 1-inch thallium-activated sodium iodide scintillation crystal. Two inches of lead shielding surrounded the sample and the scintillation detector. A DuMont 6292 photomultiplier tube was used in the scintillation detector unit. A conventional pulse height analyzer and graph recorder completed the gamma-ray spectrometer used in these experiments. The technique of using a gamma-ray scintillation spectrometer is adequately presented by Hurley (1956) and will not be described in detail in this paper.

The methods of analyses of *equilibrium* radioactive ores as presented in this paper, although developed independently, are basically those described by Hurley (1956) and Adams and co-workers (1958b). The significant contribution reported herein is, however, an extension of those techniques and may be employed to permit distinction of nonequilibrium ores from equilibrium ores. The ability to make this distinction while using only gamma-ray counting techniques is extremely important in the radiometric assaying of uranium and/or thorium ores as radio-assaying methods for these ores seldom measure gamma radiation from uranium or thorium themselves but from daughter products which are assumed to be in-equilibrium with their parents. If the daughter products are not in-equilibrium with their parents, no reliable and accurate assays can be made with any of the gamma-ray counting techniques thus far developed and described in the literature. A method which allows the determination of the state of radioactive equilibrium of an ore, however, provides a degree of reliability in assaying by indicating which ores can and which ores cannot be assayed by gamma-ray counting techniques.

## NATURAL RADIOACTIVITY

All elements found in nature with atomic numbers greater than 83 (bismuth) are radioactive. A substance, or element, is radioactive when the atoms of which

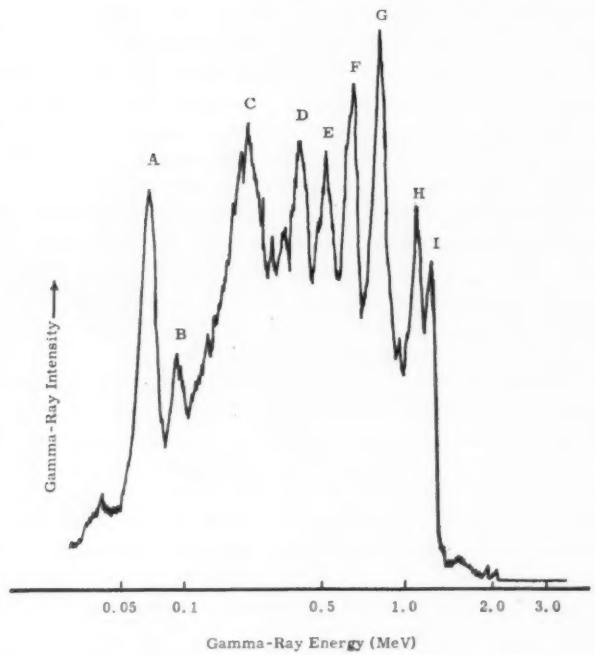


FIG. 1. The gamma-ray spectra of a group of radioactive nuclides illustrating the resolution of the equipment used in gathering data for this paper. The nuclides and energy in MeV (million electron volts) of the labeled peaks are as follows:

A. The 0.059 MeV peak of $Am^{241}$
B. The 0.087 MeV peak of $Cd^{109}$
C. An interesting photon peak caused by backscattering of primary $Co^{60}$ gamma rays in the lead shielding of the scintillation detector and appearing at about 0.200 MeV
D. The 0.393 MeV peak of $Sn^{113}$
E. The 0.510 MeV peak of $Na^{22}$
F. The 0.662 MeV peak of $Ba^{137m}$
G. The 0.840 MeV peak of $Mn^{54}$
H. The 1.170 MeV peak of $Co^{60}$
I. The 1.330 MeV peak of $Co^{60}$

it is composed disintegrate spontaneously regardless of whether or not the emission of radiation can be readily detected in the process. A radio-atom in decaying may emit one or more gamma rays or it may emit none. But, no matter how many gamma rays are emitted, each gamma photon will have a characteristic wave length or energy. Table I and Table II list the nuclides of the two major natural radioactive decay series. Included in these tables are the gamma rays emitted by each nuclide.

TABLE I. THE URANIUM DECAY SERIES

| Name of Nuclide | Atomic Number | Nuclide | Half-Life | Energy of Gamma Rays Emitted by Nuclide (MeV)[1] |
|---|---|---|---|---|
| Uranium Group | | | | |
| Uranium 1 | 92 | U 238 | $4.5\times10^{9}$ y. | 0.047 (?) |
| Uranium X1 | 90 | Th 234 | 24.1 d. | 0.093 |
| Uranium X2 | 91 | Pa 234 | 1.18 m. | 0.394, 0.782, 0.806, 0.820 |
| Uranium II | 92 | U 234 | $2.6\times10^{5}$ y. | 0.060, 0.093, 0.118 |
| Ionium | 90 | Th 230 | $8.0\times10^{4}$ y. | 0.068, 0.140, 0.190, 0.228, 0.240 |
| Radium Group | | | | |
| Radium | 88 | Ra 226 | 1,600 y. | 0.188 |
| Radon | 86 | Rn 222 | 3.825 d. | — |
| Radium A[2] | 84 | Po 218 | 3.05 m. | — |
| Radium B | 82 | Pb 214 | 26.8 m. | 0.053, 0.242, 0.259, 0.295, 0.351 |
| Radium C | 83 | Bi 214 | 17.9 m. | 0.063, 0.191, 0.426, 0.498, 0.609, 0.766, 0.933, 1.120, 1.238, 1.379, 1.520, 1.761, 1.820, 2.200, 2.420 |
| Radium C′ | 84 | Po 214 | $164\times10^{-6}$ s. | — |
| Radium D | 82 | Pb 210 | 22 y. | 0.007, 0.023, 0.032, 0.037, 0.043, 0.047, 0.065 |
| Radium E | 83 | Bi 210 | 5.0 d. | — |
| Radium F | 84 | Po 210 | 138 d. | 0.084, 0.790 |
| Radium G | 82 | Pb 206 | Stable | — |

[1] After Hollander, *et al.*, 1953.
[2] Branching decays of less than 0.2 percent are omitted.

### *Radioactive Equilibrium*

An atom that disintegrates to form another atom is called the parent and the product is called the daughter. A radio-atom is in a state of secular radioactive equilibrium with its disintegration product when the same number of atoms of the daughter nuclide disintegrate as are formed in a unit of time. Thus, in a radioactive decay series in equilibrium, the number of atoms of a nuclide being

TABLE II. THE THORIUM DECAY SERIES

| Name of Nuclide | Atomic Number | Nuclide | Half-Life | Energy of Gamma Rays Emitted by Nuclide (MeV) |
|---|---|---|---|---|
| Thorium | 90 | Th 232 | $1.4\times10^{10}$ y. | 0.055, 0.075 |
| Mesothorium 1 | 88 | Ra 228 | 6.7 y. | 0.030 |
| Mesothorium 2 | 89 | Ac 228 | 6.13 h. | 0.060, 0.135, 0.184, 0.338, 0.462, 0.533, 0.590, 0.913, 0.969 |
| Radiothorium | 90 | Th 228 | 1.9 y. | 0.087 |
| Thorium X | 88 | Ra 224 | 3.64 d. | 0.241 |
| Thoron | 86 | Rn 220 | 54.5 s. | — |
| Thorium A | 84 | Po 216 | 0.16 s. | — |
| Thorium B | 82 | Pb 212 | 10.6 h. | 0.115, 0.176, 0.238, 0.249, 0.299 |
| Thorium C | 83 | Bi 212 | 60.5 m. | 0.040, 0.144, 0.164, 0.288, 0.328, 0.432, 0.452, 0.472, 0.720, 0.830, 1.030, 1.340, 1.610, 1.810, 2.200 |
| Thorium C′ | 84 | Po 212 | $0.3\times10^{-6}$ s. | — |
| Thorium C″ | 81 | Tl 208 | 3.1 m. | 0.277, 0.510, 0.582, 0.859, 2.620 |
| Thorium D | 82 | Pb 208 | Stable | — |

formed is exactly equal to the number of atoms of that nuclide disintegrating. The number of distintegrations per unit time, therefore, is the same for each member in the decay series. As all members of the decay series do not decay at the same rate, a greater amount of the long-life nuclides will have to be present to provide the same number of disintegrations per unit time as those coming from the short-life nuclides: consequently, the amount of a nuclide present in a decay series in equilibrium is directly proportional to its half-life.

A state of non-equilibrium exists when all or part of one or more of the daughters or parents is physically removed from the decay series. If a nuclide with a short half-life is removed, equilibrium can be rapidly regained. If a nuclide with a long half-life is removed, it may be millions of years before complete equilibrium is regained between all the members of the decay chain. After uranium is deposited, it takes about $3.5 \times 10^5$ years (Hurley, 1956) to establish approximate equilibrium between all the members of the decay series mainly because of the long half-lives of two of the daughters of the uranium group of nuclides, namely $U^{234}$ and $Th^{230}$. A state of secular equilibrium, however, is regained between the first three members of the uranium group of the uranium decay series in less than a year. Assuming that $U^{234}$ has the same chemical properties as $U^{238}$, secular equilibrium is generally maintained between the first four members of the uranium series. At least in nature this should be true. As all of the daughters of $Ra^{226}$ have short half-lives, secular equilibrium is also maintained in this group of the uranium decay series when radium is present and when radon is not continuously escaping. After $Th^{232}$ is deposited, only a few decades are required to establish approximate radioactive equilibrium between all of the members of the thorium decay series as all of the daughters of $Th^{232}$ have relatively short half-lives.

## ANALYSIS OF URANIUM ORES

In the analysis of uranium ores, which in the western United States are exposed to a number of physical and chemical processes in nature that can cause separation of the various nuclides of the decay series, a gamma-ray spectrometer can be a very useful tool. Cases are known in which companies have staked claims on and have even mined intensely radioactive material only to discover it contained no uranium. The radiation was being emitted by decay daughters of the uranium ore, but the uranium nuclides themselves were not present. Having different chemical properties than other nuclides of its decay series, uranium can be leached from an ore deposit leaving the ore radioactive but devoid of valuable material.

In the uranium series the most important forms of non-equilibrium are:

(a) Radium group deficiency due to migration of radon;
(b) Daughter-product deficiency due to a lack of time to reach equilibrium or due to differential leaching of the daughter-products; and,
(c) Uranium deficiency due to differential leaching of uranium or deposition of daughter products only.

Because of this problem of radioactive non-equilibrium among nuclides of the uranium decay series, radiometric methods of analysis of uranium ores, generally, have not been accepted as a means of reliable ore analysis. After making gamma-ray spectral analyses of hundreds of uranium ores from various locations in the western United States, the author has concluded that as far as the state of radioactive equilibrium is concerned, a uranium ore can be classified as one of four types:

(a) Equilibrium ores;
(b) Radium-rich ores;
(c) Uranium-rich ores; and,
(d) Transition ores.

Figures 2, 3, 4 and 5 illustrate the gamma-ray spectra of these types of ores.

If $U^{238}$ emitted a strong gamma ray, it would be a simple matter to assay any material for this nuclide with a gamma-ray spectrometer. Although $U^{238}$ does emit a low-energy gamma ray of 0.045 MeV (million electron volts) this gamma ray is of very low intensity and is emitted at an energy that makes it very difficult to distinguish from the many other low-energy gamma rays emanating from a uranium ore at closely similar energies. A majority of ores examined in this research were either in-equilibrium or very nearly so, and this fact suggested

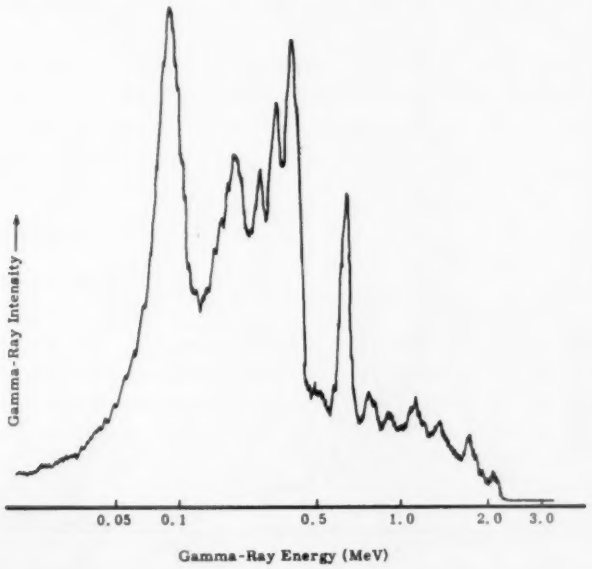


FIG. 2. The gamma-ray spectrum of an equilibrium uranium ore.

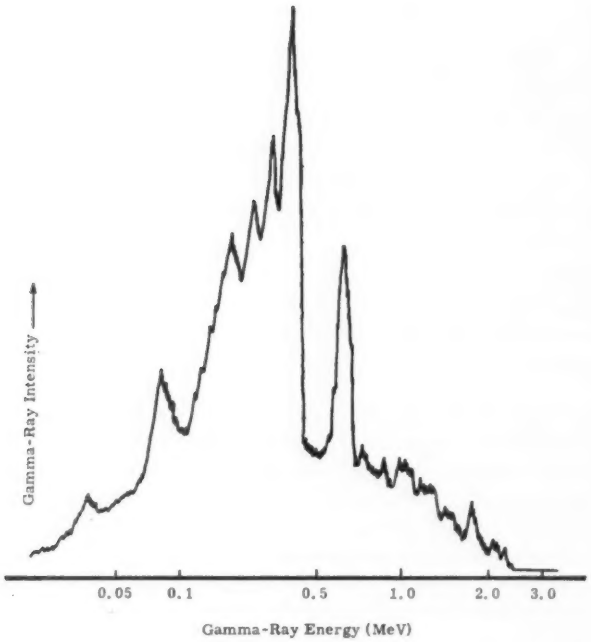


FIG. 3. The gamma-ray spectrum of the radium group of nuclides of a uranium ore.

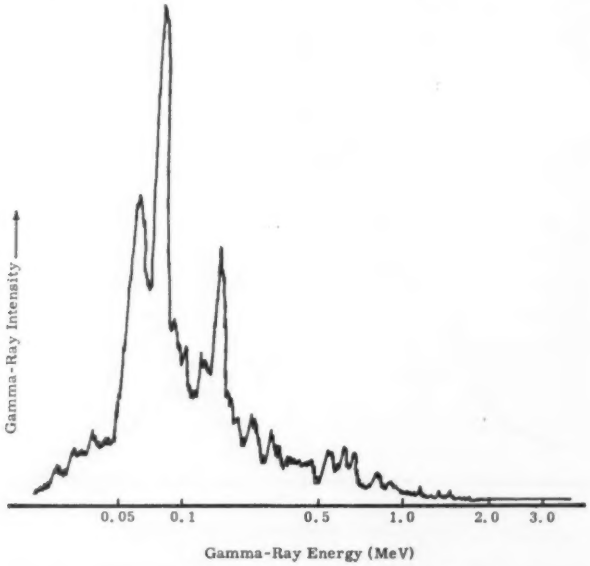


FIG. 4. The gamma-ray spectrum of the uranium group of nuclides of a uranium ($U^{238}$) ore. The uranium group of nuclides are $U^{238}$, $Th^{234}$, $Pa^{234}$, $U^{234}$, and $Th^{230}$.

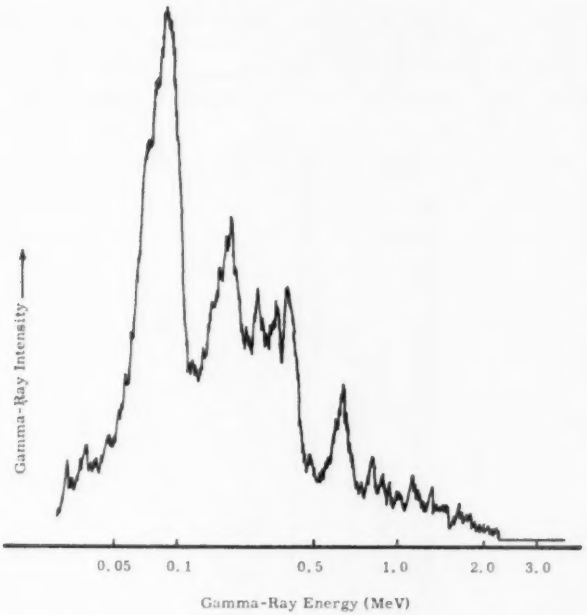


FIG. 5. The gamma-ray spectrum of a transition-type uranium ore.

that if a method could be found to determine the state of radioactive equilibrium of an ore, then it could be determined which ores could be reliably assayed by gamma counting. If the nuclides in the ore sample were found to be in-equilibrium or very nearly in-equilibrium, then it would be quite simple to make an accurate analysis of the ore for uranium. If it was found that the nuclides in the ore sample were badly out-of-equilibrium, then the ore should be analyzed for uranium by a different method.

*The Equilibrium Factor*

By taking a count of the gamma radiation on channels centered at 0.190 MeV and 0.240 MeV as illustrated in Figure 6, and computing a ratio of these count rates, a factor is obtained which can be correlated with the state of radioactive equilibrium of a uranium ore. A high value of this $C_{190}/C_{240}$ ratio (a value greater than 3.0) indicates a uranium-rich ore; a value between 3.0 and 1.3 indicates a transition-type ore; a value between 1.3 and 1.0 indicates an equilibrium ore or an ore very close to being in-equilibrium; and, a value less than 1.0 indicates a radium-rich type of ore.

At a channel setting of 0.190 MeV, gamma radiation from $Th^{230}$ of the uranium group of nuclides and from $Ra^{226}$ and $Bi^{214}$ of the radium group of nuclides is

intercepted in about equal amounts from each group in an equilibrium ore. At a channel setting of 0.240 MeV, gamma radiation from principally $Pb^{214}$ of the radium group of nuclides is intercepted. Although a 0.240 MeV gamma ray is listed for $Th^{230}$ this gamma ray is so weak it is almost undetectible.

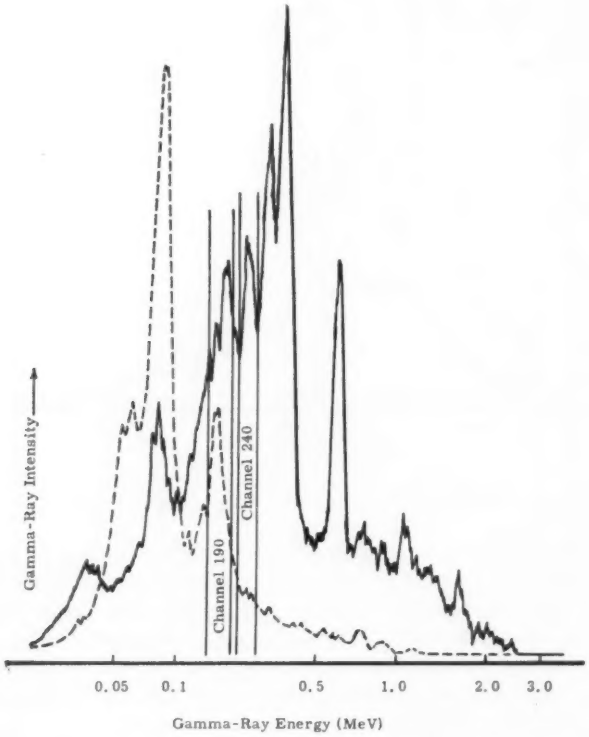


FIG. 6. The gamma-ray spectrum of the uranium group of nuclides (dashed line) superimposed on the spectrum of the radium group of nuclides (solid line). In determining the equilibrium factor of an ore, the gamma-ray intensities within channel 190 and within channel 240 are measured. The ratio, count rate of channel 190, $C_{190}$, over the count rate of channel 240, $C_{240}$, is the equilibrium factor. High values of this factor indicate a uranium-rich ore and low values indicate a radium-rich ore.

*Ore Analysis*

If an ore shows an equilibrium factor between 1.0 and 1.3, the count on the 0.190 MeV channel will be proportional to the amount of uranium in the ore sample. Hurley (1956) also suggests using the 0.190 MeV channel for uranium analysis but he did not advocate the use of an equilibrium factor. When an ore is completely in-equilibrium the count rate on any channel, or a total gamma

count of the ore for that matter, will be directly proportional to the amount of uranium in the ore. Table III shows the experimental results of uranium ore analysis with the method suggested in this paper. Although this method will not allow an accurate assay of ores that are badly out-of-equilibrium, it will allow recognition of this type of ore. As about 90 to 95 percent of the ores of western North America seem to exhibit equilibrium factors in the range between 1.0 and 1.3, this method of analysis provides a reliable radiometric method for assaying a large majority of uranium ores. The 5 to 10 percent of ores that exhibit equilibrium factors less than 1.0 or greater than 1.3 can be assayed with the usual

TABLE III. ANALYSIS OF EQUILIBRIUM URANIUM ORES

| Ore No. | Channel Countrates (Counts/Second) $C_{190}$ | $C_{240}$ | Equilibrium Factor $C_{190}/C_{240}$ | Radio[3] Assay $\%U_3O_8$ | Chem Assay $\%U_3O_8$ | Remarks (Source of Ore) |
|---|---|---|---|---|---|---|
| A-1 | 9.76 | 8.37 | 1.17 | 0.410 | 0.407 | Big Indian Wash, Utah |
| A-2 | 14.39 | 11.77 | 1.22 | 0.603 | 0.601 | Big Indian Wash, Utah |
| A-3 | 19.37 | 15.69 | 1.24 | 0.813 | 0.834 | Moab, Utah |
| A-4 | 3.90 | 3.52 | 1.11 | 0.164 | 0.170 | Standard Mines, Utah |
| A-5 | 6.17 | 5.47 | 1.13 | 0.259 | 0.251 | Blue Lizard Mine, Utah |
| A-6 | 5.22 | 4.55 | 1.15 | 0.219 | 0.224 | Hidden Splendor Mine, Utah |
| A-7 | 2.40 | 2.13 | 1.13 | 0.101 | 0.100 | AEC Standard Ore |
| A-8 | 51.56 | 44.07 | 1.17 | 2.165 | 2.15 | AEC Standard Ore |
| A-9 | 8.67 | 7.45 | 1.16 | 0.364 | 0.374 | Big Indian Wash, Utah |
| A-10 | 10.68 | 9.00 | 1.19 | 0.448 | 0.452 | Hidden Splendor Mine, Utah |
| A-11 | 6.05 | 5.09 | 1.19 | 0.254 | 0.25 | AEC Standard Ore |
| A-12 | 36.36 | 29.01 | 1.17 | 1.527 | 1.513 | Lisbon Uranium, Utah |
| A-13 | 100.65 | 88.55 | 1.14 | 4.23 | 4.29 | AEC Standard Ore |
| A-14 | 25.30 | 21.60 | 1.17 | 1.062 | 1.103 | Moab, Utah |

[3] In an equilibrium uranium ore the count rate on any channel, $C_x$, is proportional to the amount of uranium in the ore sample, or percent $U_3O_8 = K_x \cdot C_x$. In this report a channel centered at 190 MeV was used in the uranium analysis, or percent $U_3O_8 = K_{190} \cdot C_{190}$. For the particular sample geometry and spectrometer settings used in gathering data for Table III, the value of $K_{190}$ was determined to be 0.042/(counts per second per percent $U_3O_8$).

fluorometric or chemical means. This gamma-ray spectral method of analysis retains all the advantages of radiometric assaying such as large samples (to 1,000 gm or more), no fine grinding (crushing to $\frac{1}{2}$ inch is sufficient), analyses within a few minutes of receipt of the ore sample, and the use of no chemical reagents.

Table IV lists a number of equilibrium ores and a number of various types of non-equilibrium ores that illustrate how the value of the equilibrium factor can be used to recognize the non-equilibrium ores. Also listed in Table IV are a number of uranium-thorium composite ores. The composite-ore factor listed in Table IV is used to recognize uranium-thorium ores and will be explained in greater detail later in this paper. Although thorium is generally not a constituent of uranium ores in the United States, it frequently is found in uranium ores in other countries and creates a problem in attempts to correlate scintillation count rates with the uranium content in such ores.

TABLE IV. RECOGNITION OF EQUILIBRIUM AND NON-EQUILIBRIUM ORES BY THE VALUE OF THE EQUILIBRIUM FACTOR

| Ore No. | Channel Countrates (Counts/Second) $C_{190}$ | $C_{240}$ | $C_{351}$ | Equilibrium Factor $C_{190}/C_{240}$ | Composite Ore Factor $C_{240}/C_{351}$ | Radio Assay $\%U_3O_8$ | Chem Assay $\%U_3O_8$ | Remarks (Type of Ore) |
|---|---|---|---|---|---|---|---|---|
| B-1 | 39.56 | 41.98 | 70.81 | 0.96 | 0.59 | — | 0.00 | Radium-rich ore |
| B-2 | 35.33 | 36.73 | 62.74 | 0.94 | 0.59 | — | 0.002 | Radium-rich ore |
| B-3 | 3.50 | 2.84 | — | 1.23 | — | 0.15 | 0.18 | Equilibrium ore |
| R-4 | 228.36 | 250.28 | 384.03 | 0.91 | 0.65 | — | 0.22 | Uranium-deficient |
| R-5 | 11.48 | 2.41 | — | 4.76 | — | 2.41[4] | 2.27 | Uranium-rich |
| R-6 | 47.80 | 140.60 | 55.51 | 0.34 | 2.53 | — | 0.04 | Thorium ore |
| R-7 | 62.52 | 9.87 | — | 6.34 | — | 13.5 | 14.0 | Uranium-rich ore |
| R-8 | 8.71 | 9.50 | 15.20 | 0.92 | 0.63 | — | 0.022 | Uranium Mill Tails |
| R-9 | 27.98 | 22.86 | — | 1.22 | — | 1.17 | 1.17 | Equilibrium ore |
| R-10 | 9.17 | 26.65 | 10.21 | 0.34 | 2.61 | — | 0.03 | U-Th Composite ore |
| R-11 | 122.66 | 180.94 | 195.03 | 0.65 | 0.93 | — | 0.01 | U-Th Radium Groups |
| R-12 | 6.58 | 0.86 | — | 7.66 | — | 1.44 | 1.40 | Uranium-rich ore |
| R-13 | 14.53 | 11.82 | — | 1.23 | — | 0.610 | 0.608 | Equilibrium ore |
| R-14 | 203.15 | 312.32 | 308.20 | 0.65 | 1.01 | — | 0.00 | U-Th Radium Groups |
| R-15 | 29.90 | 33.97 | 51.30 | 0.88 | 0.66 | — | 0.000 | Radium-rich ore |

[4] The value of the conversion factor used to convert from counts per second to percent $U_3O_8$ for uranium-rich ores is 0.021 or exactly one half that of the conversion factor for an equilibrium uranium ore.

### ANALYSIS OF THORIUM ORES

Figure 7 illustrates the gamma-ray spectrum of a chemically refined thorium oxide less than 20 years in age and Figure 8 illustrates the gamma-ray spectrum of a pre-Quaternary thorium ore. The close similarity of these two spectra is evidence that, on deposition, $Th^{232}$ does quickly attain secular radioactive equilibrium with its daughters. In nature, then, it would be expected that thorium was always in equilibrium with its daughters. With equilibrium thorium ores the total count of the gamma radiation will be proportional to the thorium in the ore as will be the count rate under any peak in the thorium spectrum. The experimental results of equating the count rate obtained with a gamma-ray spectrometer channel set at 0.238 MeV with the $ThO_2$ in an ore sample are shown in Table V.

Uranium is generally found with thorium in nature in a ratio of about ten parts of thorium to one part of uranium. The ores listed in Table V were selected for this experiment because of the relatively small amount of uranium contamination.

Checking the state of equilibrium of a thorium ore, uncontaminated with uranium, is relatively simple. Table II indicates that $Th^{232}$ itself emits gamma radiation with an energy of 0.075 MeV. This gamma ray is relatively intense and a ratio of the count rates of channels centered at 0.075 MeV and 0.238 MeV can be used as a thorium ore equilibrium factor. Values for this factor, $C_{075}/C_{238}$, of equilibrium thorium ores generally range between 0.65 to 0.75 except for high-

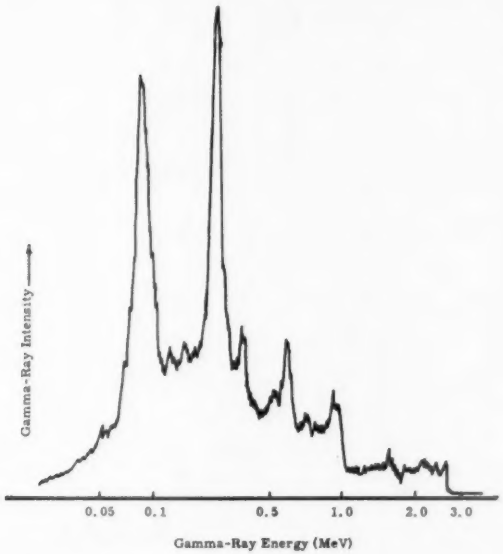


FIG. 7. The gamma-ray spectrum of a chemically refined thorium oxide which is less than 20 years old.

grade ores in which there is appreciably more absorption in the ore itself of the lower-energy gamma radiation on the 0.075 MeV channel than on the 0.238 MeV channel. Sample self-absorption will tend to decrease the value of the thorium ore equilibrium factor and this phenomenon is the cause of the low values of the equilibrium factors for ores C-2 and C-5 in Table V.

TABLE V. THORIUM ORE ANALYSIS RESULTS

| Ore | Channel Countrates | | | | Equilibrium Factor $C_{190}/C_{238}$ | Composite Ore Factor $C_{238}/C_{581}$ | Thorium Equil. Factor $C_{075}/C_{238}$ | Radio Assay[6] %$ThO_2$ | Chem Assay %$ThO_2$ | Chem Assay %$U_3O_8$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | $C_{075}$ | $C_{190}$ | $C_{238}$ | $C_{581}$ | | | | | | |
| | (Counts/Second) | | | | | | | | | |
| C-1 | 15.38 | 6.09 | 17.90 | 7.73 | 0.34 | 2.32 | 0.74 | 0.65 | 0.69 | Tr |
| C-2 | 54.45 | 42.05 | 127.35 | 45.00 | 0.33 | 2.83 | 0.44 | 4.88 | 5.00 | 0.20 |
| C-3 | 10.60 | 4.50 | 13.65 | 4.80 | 0.33 | 2.85 | 0.74 | 0.52 | 0.40 | 0.01 |
| C-4 | 25.40 | 12.51 | 34.40 | 13.72 | 0.36 | 2.51 | 0.64 | 1.28 | 1.44 | 0.05 |
| C-5 | 82.00 | 48.40 | 147.00 | 51.40 | 0.33 | 2.86 | 0.49 | 5.64 | 5.36 | 0.02 |
| C-6 | 17.44 | 8.07 | 24.95 | 8.12 | 0.32 | 3.07 | 0.65 | 0.97 | 1.00 | 0.04 |
| C-7 | 4.23 | 1.65 | 4.93 | 1.78 | 0.34 | 2.77 | 0.80 | 0.19 | 0.20 | 0.01 |
| C-8 | 9.43 | 4.00 | 12.65 | 4.15 | 0.32 | 3.05 | 0.69 | 0.50 | 0.50 | 0.02 |
| C-9 | 15.20 | 6.58 | 21.23 | 6.70 | 0.31 | 3.17 | 0.72 | 0.85 | 0.80 | 0.03 |

[6] In an equilibrium thorium ore the count rate on any channel, $C_x$, is proportional to the amount of thorium in the ore sample. In determining the radiometric assays for $ThO_2$ in Table V the count rate obtained with the channel centered at 0.238 MeV was used, or, percent $ThO_2 = K_{238}C_{238}$. For the particular sample geometry and spectrometer settings used in gathering data for Table V, the value of $K_{238}$ was determined to be 0.0403/(counts per second per percent $ThO_2$).

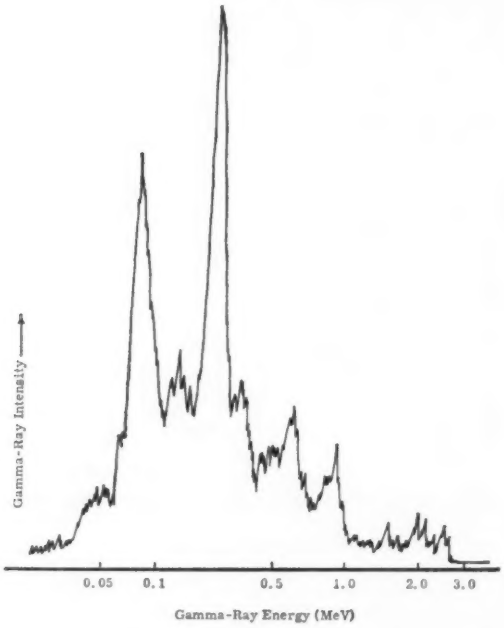


FIG. 8. The gamma-ray spectrum of a pre-Quarternary thorium ore. The similarity of this spectrum with the spectrum of a recently refined thorium oxide, as shown in Figure 7, is evidence of the relatively short time required for all the nuclides of the $Th^{232}$ decay series to reach a state of secular radioactive equilibrium.

## ANALYSIS OF URANIUM-THORIUM COMPOSITE ORES

### *Direct Determination of Uranium-Thorium Ratios in Rocks*

For purposes of strata recognition or correlation, the determination of the uranium-thorium ratio of rocks is generally more important than a specific assay for either uranium or thorium. Assuming that uranium and thorium are in-equilibrium with their respective daughter products, Adams and co-workers (1958b) and Brannon and co-workers (1956) suggest counting on the 2.62 MeV gamma ray emitted by $Tl^{208}$ of the $Th^{232}$ decay series for a thorium assay and by counting on the 1.76 MeV gamma ray from $Bi^{214}$ of the uranium series for a uranium assay. In this way there will be no interference from gamma radiation of the 1.4 MeV gamma ray emitted by $K^{40}$ which also might be present in the rock sample. Disadvantages of these methods are the relatively low count rates obtained with uranium or thorium containing materials at 1.76 MeV and 2.62 MeV.

Hurley (1956) suggests counting with channels centered at 0.168 MeV, 0.238 MeV, and 1.39 MeV and using a series of simultaneous equations to com-

pute the amount of uranium, thorium, and potassium, respectively, in materials being assayed. Hurley (1956) also describes a method of determining the uranium-thorium ratio of rocks directly by computing the ratio of count rates at 0.18 MeV and 0.238 MeV and using a graph showing a plot of this countrate ratio vs the uranium-thorium ratio.

An alternative method of analysis will also yield a uranium-thorium ratio directly. If a count is taken with channels centered at 0.238 MeV and 0.351 MeV

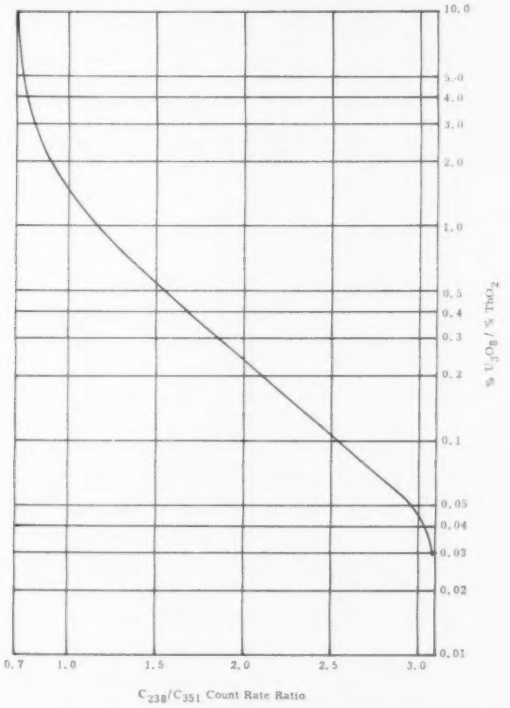


FIG. 9. The channel 238-channel 351 countrate ratio vs the uranium-thorium ratio of a composite ore.

and a ratio of these counts computed, then, the graph of Figure 9, which was obtained from experimental data, can be used to determine the uranium-thorium ratio of the rock sample. Figure 10 illustrates the gamma-ray spectrum of an ore containing 1.92 percent $U_3O_8$ and 1.07 percent $ThO_2$ with the 0.238 MeV and 0.351 MeV channels indicated by vertical lines. The nuclides emitting gamma rays at these energies are principally $Pb^{212}$ of the $Th^{232}$ decay series at 0.238 MeV and $Pb^{214}$ of the $U^{238}$ decay series at 0.351 MeV. The backscatter gamma radia-

tion from $K^{40}$, which will be about equal on both of these channels, can be ignored if it constitutes a minor part of the total radiation intercepted. If $K^{40}$ contributes a large share (five percent or more) of the radiation on these channels, an adjustment must be made for this contribution. Hurley (1956) and Adams and co-workers (1958b) describe how this adjustment can be made.

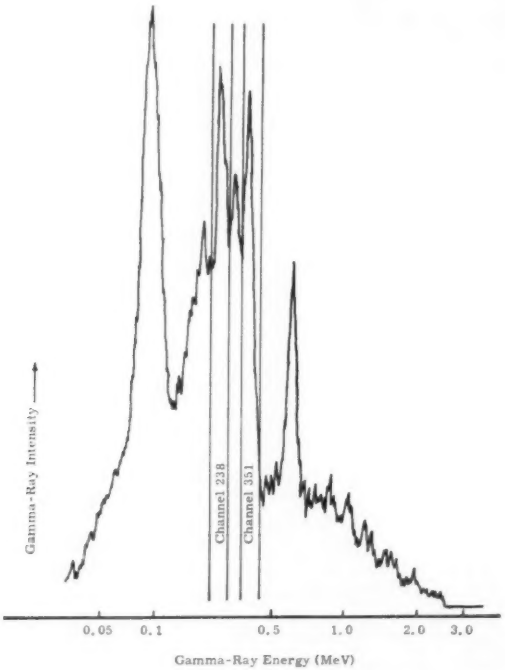


FIG. 10. The gamma-ray spectrum of a uranium-thorium composite ore. This particular ore contains 1.92 percent $U_3O_8$ and 1.07 percent $ThO_2$. The channels used to determine the composite-ore factor are indicated by the vertical pairs of lines.

*Analyses for Uranium and Thorium in Composite Ores*

Should an analysis for uranium or thorium in a composite ore be desired, the following method can be used. Assuming that the only gamma radiation emitted by a sample comes from $U^{238}$ and $Th^{232}$ and their daughter products in radioactive equilibrium with each other, the total gamma activity, $C_{238}$, at 0.238 MeV can be expressed as:

$$C_{238} = C_{238T} + C_{238U} \qquad (1)$$

where $C_{238T}$ is the contribution from the thorium series and $C_{238U}$ is the contribution from the uranium series. This analysis will also ignore any gamma-ray count contribution from the $U^{235}$ decay series which will be less than 1/100 of that coming from the $U^{238}$ and the $Th^{232}$ series and will, in any case, be proportional to the contribution of the $U^{238}$ series as these two series, the $U^{238}$ and the $U^{235}$, are found in a constant ratio in nature (Rankama, 1954). The effects of sample self-absorption can also be neglected in materials of a grade less than two percent of either uranium or thorium; consequently, the gamma-ray count from each series at 0.238 MeV will be directly proportional to the amount of uranium, U, and thorium, Th, present, or

$$C_{238} = K_t(\mathrm{Th}) + K_u(\mathrm{U}), \tag{2}$$

$$C_{238}/(\mathrm{Th}) = K_t(\mathrm{Th})/(\mathrm{Th}) + K_u(\mathrm{U})/(\mathrm{Th}) = K_t + K_u(\mathrm{U/Th}) \tag{3}$$

and

$$(\mathrm{Th}) = C_{238}/[K_t + K_u(\mathrm{U/Th})]. \tag{4}$$

The numerical value of the conversion factors, $K_t$ and $K_u$, will be a function of the sample size and geometry and gamma-ray spectrometer window width. For purposes of this report, $K_t = 24.8$ counts per second per percent $ThO_2$ and $K_u = 20.5$ counts per second per percent $U_3O_8$.

To solve equation (4), the (U/Th) ratio must be taken from Figure 9 after computing the $C_{238}/C_{351}$ ratio. The percent of uranium is computed by simply multiplying the U/Th ratio by the percent Th as obtained in equation (4). This method, of course, will only yield the equivalent percent of uranium and thorium, that is the actual percent of $Th^{232}$ and $U^{238}$ if the decay series are in radioactive equilibrium. The state of equilibrium of each series can be checked by determining the count at 0.075 MeV for the $Th^{232}$ series and at 0.190 MeV for the $U^{238}$ series and by computing equilibrium ratios as suggested earlier in this paper.

Table VI lists the experimental results of thorium and uranium ore analysis by means of this method. Also included in this table are results obtained in an attempt to analyze materials which contain all the radium group of daughters of a uranium ore and all the daughters of a thorium ore except $Th^{232}$ itself. The gamma spectrum of this type of material, illustrated by ore samples D-6 and D-8 in Table VI, is shown in Figure 11. Such materials are commonly found in hot springs deposits where precipitating barium or strontium sulphates will scavenge radium isotopes from solution without affecting either the uranium or the thorium in solution. Although equation (4) and Figure 9 would yield a substantial equivalent uranium and thorium assay for ore samples D-6 and D-8, the calculation of the uranium and thorium equilibrium factors will indicate there probably is no $U^{238}$ or $Th^{232}$ in the sample. The equilibrium factors for these types of ores are *in italics* in Table VI.

TABLE VI. RESULTS OF ASSAYS ON COMPOSITE ORES

| Ore No. | Channel Countrates (Counts/Second) $C_{075}$ | $C_{190}$ | $C_{238}$ | $C_{351}$ | Equilibrium Factor $C_{190}/C_{238}$ | Composite Ore Factor $C_{238}/C_{351}$ | Thorium Equil. Factor $C_{075T}/C_{238T}$ | Uranium Equil. Factor $C_{190U}/C_{240U}$ | Radio Assay $\%ThO_2$ | Chem Assay $\%ThO_2$ | Radio Assay[6] $\%U_3O_8$ | Radio Assay[7] $\%U_3O_8$ | Chem Assay $\%U_3O_8$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D-1 | 44.50 | 27.21 | 28.95 | 36.40 | 0.94 | 0.80 | 0.73 | 1.21 | 0.34 | 0.33 | 1.00 | 1.04 | 1.00 |
| D-2 | 18.18 | 13.02 | 37.55 | 13.42 | 0.35 | 2.80 | 0.41 | 1.43 | 1.44 | 1.13 | 0.10 | 0.11 | 0.14 |
| D-3 | 64.05 | 35.37 | 89.09 | 38.15 | 0.40 | 2.34 | 0.58 | 1.31 | 3.22 | 2.68 | 0.43 | 0.51 | 0.46 |
| D-4 | 45.60 | 27.48 | 33.20 | 37.10 | 0.83 | 0.90 | 0.57 | 1.11 | 0.52 | 0.50 | 0.99 | 1.00 | 1.00 |
| D-5 | 23.20 | 12.22 | 28.85 | 12.89 | 0.42 | 2.24 | 0.66 | 1.48 | 1.03 | 1.00 | 0.17 | 0.20 | 0.20 |
| D-6 | 97.52 | 122.66 | 180.94 | 195.03 | 0.65 | 0.93 | *−1.40* | *0.94* | — | Nil | — | — | 0.01 |
| D-7 | 25.32 | 18.70 | 34.94 | 23.33 | 0.54 | 1.50 | 0.26 | 1.10 | 0.98 | 0.78 | 0.51 | 0.49 | 0.49 |
| D-8 | 48.74 | 58.41 | 100.76 | 89.47 | 0.58 | 1.13 | *− .73* | *0.75* | — | Nil | — | — | Nil |
| D-9 | 84.61 | 53.47 | 71.29 | 70.44 | 0.75 | 1.01 | 0.42 | 1.15 | 1.33 | 1.07 | 1.86 | 1.84 | 1.82 |
| D-10 | 20.35 | 9.51 | 26.85 | 10.09 | 0.35 | 2.66 | 0.68 | 1.28 | 1.01 | 1.00 | 0.08 | 0.10 | 0.10 |
| D-11 | 18.43 | 8.64 | 26.15 | 9.02 | 0.33 | 2.90 | 0.65 | 1.07 | 1.00 | 1.00 | 0.06 | 0.06 | 0.06 |

[6] Radio assay by equation (4) method.
[7] Radio assay by equation, $\%U_3O_8 = 0.042\ C_{190U}$.

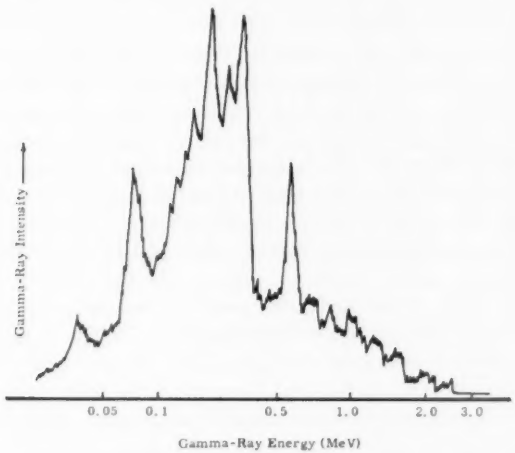


FIG. 11. The gamma-ray spectrum of a sample of material from a deposit of the radium nuclides and their daughters of both the uranium and the thorium decay series. The mother nuclides, $U^{238}$ and $Th^{232}$, are absent from this material.

## OTHER POTENTIAL APPLICATIONS FOR A GAMMA-RAY SPECTROMETER

### *Analysis of Potash Ores*

Potash ores can be assayed by setting a gamma-ray spectrometer to count the 1.4 MeV gamma ray of the naturally occurring nuclide, $K^{40}$. In nature $K^{40}$ is proportional to the total potassium content of the ore. In the field, where the use of heavy shielding for the scintillation detector may be impractical, background countrates may be high. In using a lightly shielded scintillation detector for gamma-ray counting, it is not uncommon for 90 percent of the total count to be background counts with only 10 percent of the count produced by the element in question. Using a gamma-ray spectrometer for potash analysis, the background count can be largely eliminated and a more reliable and accurate assay of the potash ore can be obtained in a much shorter count time.

In well logging in potash deposits, if there is a non-uniform contamination of the potash with uranium or thorium decay daughters, this factor in the radio-assaying of the potash containing formation can be recognized by gamma-ray spectroscopy and adjustments can be made. Work by Brannon and Osoba (1956) demonstrated that techniques and equipment available in 1956 could be used to determine the relative concentrations of uranium, thorium, and potassium in underground strata by means of borehole gamma-ray spectral analysis; equipment available at the present time will allow absolute assays to be made for potassium.

*Neutron-Activation of Non-Radioactive Elements*

In the analysis of ores for various nuclides which are not naturally radioactive, a technique of neutron-activation and gamma-ray spectral analysis offers an approach which has not yet been fully explored. When an atom is bombarded by neutrons, one of several reactions may occur. In most of these reactions, secondary radiation is emitted by the target atom. Often the secondary emission is in the form of gamma radiation and for a specific nuclear species and reaction, this gamma radiation is of a characteristic wave length.

The thermal neutron cross-sections of many elements of interest in mineral exploration such as molybdenum, vanadium, manganese, cobalt, antimony, copper, tungsten, gold, silver, cadmium, and mercury, to mention a few, would allow activation of these elements (Friedlander, et al., 1955). Figure 12 shows the gamma-ray spectra of gold and of copper after neutron-activation. A rather sharp photon peak is obtained in each case, and the height of these peaks, which is a measure of the countrate or intensity of radiation, is directly proportional to the amount of gold or copper present in the sample.

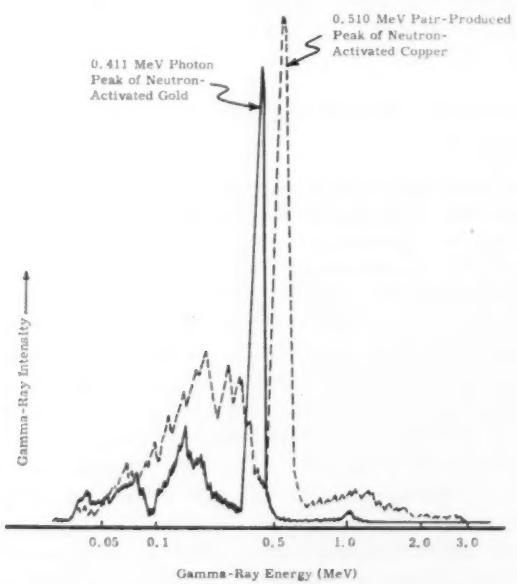


FIG. 12. The gamma-ray spectrum of neutron-activated gold (solid line) superimposed on the spectrum of neutron-activated copper (dashed line). The major photon peaks of these two spectra could be easily resolved with presently available spectrometers.

*Borehole Analyses*

Several published papers (Muench, et al., 1957; Baker, 1957; Caldwell, et al., 1958) describe methods of using neutron-activation and gamma-ray spectral analysis to identify such materials as sulphur, chlorine, calcium, hydrogen, silicon, oxygen, and magnesium in earth materials surrounding a simulated borehole. Results of successful tests to correlate countrates produced by neutron-activated sulphur and chlorine with the concentration of these elements in the earth materials are also described (Muench, et al., 1957). The technique of using a scintillation detector in a borehole is covered by DiGiovanni (DiGiovanni, et al., 1953).

Unfortunately, backscattering and Compton-effect reactions will cause considerable difficulty in developing a technique to use effectively neutron-activation and gamma-ray spectroscopy for borehole quantitative analysis of low-energy gamma-ray emitters such as copper or gold. Figure 13 shows the spectrum of a uranium ore sample at the surface. Degraded gamma rays that appear at lower energies than the primary gamma emissions do not noticeably confuse the the spectrum in this case. Figure 14 illustrates a gamma-ray spectrum of a

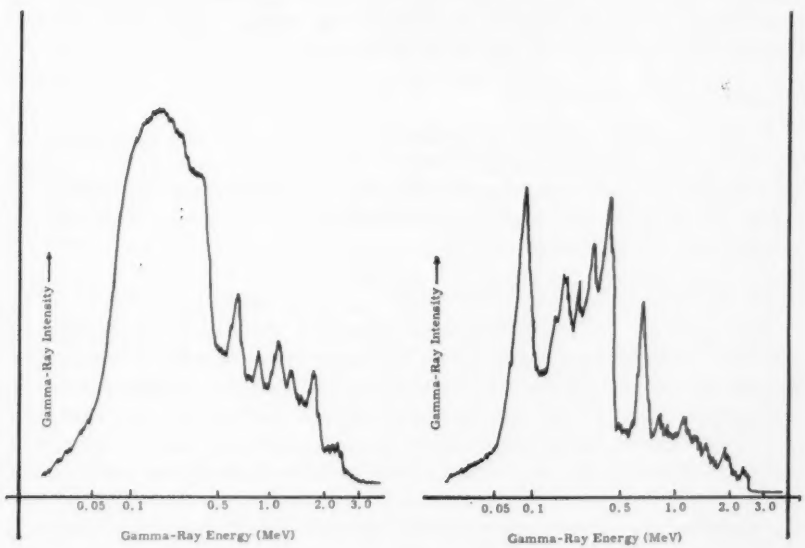


FIG. 13. The gamma-ray spectrum of a uranium ore sample at the surface of the earth. The intensity scales are not common in Figures 13 and 14.

FIG. 14. The gamma-ray spectrum of a uranium ore with the scintillation detector in a borehole within the orebody.

uranium ore obtained with the scintillation detector down a borehole. The large increase of degraded gamma rays appearing in the low-energy region of the spectrum greatly complicates analysis of this spectrum.

*Tracer Studies*

An outstanding potential use of the gamma-ray spectrometer will be in studying the permeability of rock and ores under natural conditions, and in studying the flow patterns established by fluids in given formations. Tagged molecules and particles of varying physical sizes and differing chemical properties can be used to study the pore size in a formation as well as the chemical exchange properties of the rock. With a gamma-ray spectrometer, multiple tracer experiments could be run for greater efficiency. Presently, radioactive tracers with simple gamma-ray counting are used in locating zones of permeability in oil wells (Flagg, et al., 1955).

In studies of the permeability of orebodies of metallic minerals in preparation for in-place leaching of the valuable constituents of these deposits, the use of radioactive tracers of varying physical and chemical properties will be invaluable. In-place leaching of low-grade orebodies offers a tremendous potential in reducing the production cost of certain ores. Instead of removing 100 percent of the rock in an orebody, only the valuable constituents would be removed and recovered. The materials-handling cost reductions are evident.

*Beach Sand Flow Studies*

One recent application of the gamma-ray spectrometer was in determining the direction of sand flow along the beaches of northern California by following the movement of uranium-thorium mineral grains which enter the coast sands at a specific location and which have a characteristic uranium-thorium ratio by which they can be recognized.

*Strata Identification and Correlation Studies*

The naturally occurring radioactive elements are found in sediments in concentrations which are dependent on the source material of the sediment, and, through the chemical characteristics of these nuclides, on conditions of deposition: consequently, individual concentrations may be diagnostic for particular formations. These concentrations, if measured in situ, could lead to a powerful tool for correlation and for reflecting environmental conditions under which sedimentation took place (Brannon, et al., 1957; Murray, et al., 1958).

According to a hypothesis by Hans Pettersson (1939), the ratio of uranium to thorium in a basin sediment should be a function of the distance from a continental mass at which sedimentation occurs because uranium and thorium ions have differing chemical behaviors, which are, to a degree, dependent on the pH of the transporting solutions. Supporting this hypothesis, Adams (1958a) describes the use of uranium-thorium ratios of rocks as indicators of sedimentary

processes and environments under which certain sedimentary rocks are formed.

In attempts to use gamma-ray logs as tools for strata correlation, difficulties are often encountered because of seemingly erratic variations of the total gamma count. Individual uranium, thorium and potassium determinations in the borehole would have great value in resolving these anomalies of total radioactivity that often detract from the utility of the conventional gamma-ray log.

## PRESENT STATUS OF THE USE OF GAMMA-RAY SPECTROMETERS

Gamma-ray spectrometers are not by any means common pieces of equipment in the exploration industry, which probably stems from the fact that these instruments have been in use for a comparatively short period of time and that they are not standardized pieces of equipment. Probably the greatest barrier to overcome in expanding the use of the gamma-ray spectrometer will be in educating personnel as to how it can be used and in the technique of using it.

The cost of a gamma-ray spectrometer may be another deterrent to its rapid acceptance as a mineral exploration tool. A good single-channel spectrometer with scintillation detector, scaler, and graphic recorder can be purchased for about $3,500. Such a spectrometer would be adequate for a small laboratory.

The potential utilization of the gamma-ray spectrometer in mineral exploration has hardly been touched. As this instrument is developed and as personnel are educated in its proper use, we should see it take a place in any well-equipped mineral exploration laboratory along with such tools as the x-ray fluorescence and x-ray diffraction spectrometers.

## CONCLUSIONS

Gamma-ray spectrometers can be powerful tools in mineral exploration. At present, this equipment is used to make rapid and reliable analyses for potassium, uranium, and thorium in ores or rock materials. Uranium-thorium ratios of rocks, which are important in strata recognition and correlation studies, can be made directly with a gamma-ray spectrometer without individual analyses for either uranium or thorium.

The erratic behavior of total gamma-ray well logs can often be resolved by gamma-ray spectral analyses of the radiation from the anomalous zones. While downhole assaying for such common rock constitutents as calcium, sulphur, chlorine, hydrogen, silicon, oxygen, and magnesium can be done with a gamma-ray spectrometer, the techniques presently used need much refinement before they become practical field tools.

Studies involving simple radioactive tracers can be greatly facilitated by use of a gamma-ray spectrometer while studies involving the use of multiple tracers are made possible through the use of this equipment. As information about the potential uses of this equipment is disseminated we should see the gamma-ray spectrometer take a place in mineral exploration laboratories along with the x-ray diffraction and x-ray fluorescence spectrometers.

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A great number of geople gave me very real help in developing techniques described in this paper and in the preparation of it. Certainly of greatest help was Professor L. E. Shaffer who established the radioactivity laboratory in the Department of Mineral Technology. George Gordon of the Department of Mineral Technology was instrumental in developing the techniques used in this research. Professors Stanley Ward and L. E. Shaffer helped in the preparation of the manuscript.

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1077–1093, 12 FIGS.

# AN ELECTRICAL RESISTIVITY SURVEY FOR GROUND WATER*

TSVI MEIDAV†

## ABSTRACT

An electrical resistivity survey was carried out in Grundy, Chariton, and Carroll Counties, Missouri, in connection with a ground water project of the Missouri Geological Survey. The aim of the project was to locate buried channels under the glacial cover.

The resistivity data obtained was interpreted both empirically and quantitatively. The empirical method was found to be satisfactory wherever the uniformity of electrical properties was maintained by either the glacial cover or bedrock, and the resistivity contrast was high. The quantitative technique used most commonly in this study was Spicer's (1956) modification of Hummel's (1932) procedure, used in conjunction with standard two-, three-, and four-layer master curves. The limitations of the quantitative methods of interpretation are indicated in a series of resistivity distribution curves.

## INTRODUCTION

This electrical resistivity investigation was carried out in connection with a drilling program which the Missouri Geological Survey conducted in northern Missouri during 1955–57. The aim of the drilling program was to find new sources of potable ground water in buried channels below the glacial cover.

The object of this investigation was to determine whether (1) the electrical resistivity method might be useful in delineating bedrock topography, and whether (2) the method would help delineate glacial stratigraphy in the study area. It was considered that the first problem could be solved if the glacial drift should exhibit electrical properties which are distinctly and unequivocally different than those of the bedrock. The second problem was considered to be dependent upon the range of resistivities of each lithologic unit within the glacial drift.

Northern central Missouri is underlain by Pennsylvanian rocks which dip gently in a southwesterly direction. These rocks consist of a large number of thin beds of limestone, sandstone, and shale. The maximum thickness of the glacial drift covering the bedrock is about 400 ft. The glacial cover thins southward and its thickness is negligible south of the Missouri River. The electrical resistivity study covered Chariton and Carroll Counties and a part of Grundy County (Figure 1).

## METHODS OF INTERPRETATION

Resistivity curves may be interpreted by either empirical or quantitative methods. The empirical method used here is based on a constant correlation of field resistivity curves with resistivity curves that were obtained at wells for which logs were available, or at thick road cuts. This empirical method was found to be satisfactory wherever uniformity of electrical properties was main-

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FIG. 1. Area covered by the resistivity study.

tained by either glacial drift or bedrock, and resistivity contrast was high, so that only depth-to-bedrock need be considered as a variable. There the resistivity contrast is low or the number of layers is large, the change in the slope of the curve may not be capable of visual interpretation. Figure 2 illustrates an example of a successful empirical interpretation which helped locate accurately a buried channel, as was shown by subsequent drilling.

The quantitative methods used here are based on either comparison of the field curve with a set of master curves or on mathematical analysis of the curves obtained. The advantage of these methods lies in the fact that they yield an approximately true resistivity value of each lithologic unit, as well as the depth-to-bedrock. These true resistivity values allow a critical examination of the applicability of the resistivity method in northern Missouri in general.

Roman's (1934) superposition method is a quick and efficient method for the two-layer case. However, the number of curves which exhibited a two-layer appearance was very small. Roman's master curves were used in conjunction with Hummel's (1932) approximation method, whereby a three-layer curve is resolved into two two-layer curves wherever no three-layer master curve is available. Wetzel and McMurry (1937), and Mooney and Wetzel (1956) master curves for the three- and four-layer earth were used frequently, but these methods

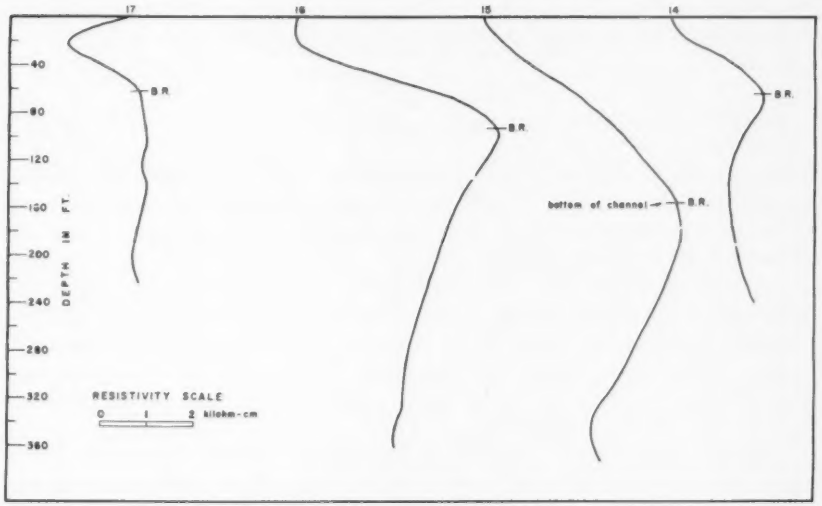


FIG. 2. Example of an empirical interpretation, which was used to locate a buried channel in Grundy County, Missouri.

did not fit a large number of field curves because of the obviously large number of permutations of resistivity within a four-layer earth, which is considerably greater than the number of master curves computed. The best method and the one most commonly used in this study is the one due to Hummel.

## HUMMEL'S METHOD

Hummel (1932) showed that two layers of different resistivities may be combined into one, provided that the thickness of the second layer is large compared with the thickness of the first.

The resistivity of the composite layer is given by Kirchoff's law for resistors in parallel:

$$\frac{d}{\rho_{\text{comp}}} = \frac{d_1}{\rho_1} + \frac{d_2}{\rho_2}, \tag{1}$$

where

$d_1$, $\rho_1$ are the thickness and resistivity of the first layer,
$d_2$, $\rho_2$ are the thickness and resistivity of the second layer,
$d$, $\rho_{comp}$ are the thickness and resistivity of the composite layer.

Thus, a three-layer earth may be mathematically reduced to a two-layered one by combining the upper two layers by means of Hummel's procedure and then solving the new curve as a two-layer case by means of Roman's master curves. Similarly, where $d_3 \gg d_2 \gg d_1$ and $\rho_1 > \rho_2 \lesssim \rho_3$, the top three layers may be combined into a single layer by means of the generalized relationship

$$\frac{d}{\rho_{comp}} = \sum_{i=1}^{n} \frac{d_i}{\rho_i}, \tag{2}$$

where $n$ is the number of layers to be combined. The requirement that the resistivities of consecutively deeper layers should decrease relative to the layer above is a consequence of Watson and Johnson's (1938) analysis, which indicated that Hummel's approximation does not give a good fit in the three-layer, maximum-type curves. In such cases, the two-layer master curve approaches the lower section of the three-layer curve only at very great distances. The approximation was found to be sufficiently accurate only when the intermediate layers had a lower resistivity than the top and bottom layers. Fortunately, this constraint is not too limiting, as the majority of curves obtained in this study are of the required type.

Spicer's (1956) modification of Hummel's method has the attractive feature of being self-corrective. That is, a wrong depth interpretation will generally not yield a good fit of the master curve with that section of the field curve which corresponds to the bottom layer. To demonstrate the self-corrective features of Hummel's method it will be first applied to the analysis of a three-layer master curve taken from Wetzel and McMurry (1937). The resisitivity ratios of the theoretical curve are 1:1/10:3 and thickness ratio is 1:3 (Figure 3). The bottom of the second layer is, as usual in this set of curves, above the abscissa value of 8. The resistivity of the first layer is determined from very short electrode spacing and is taken to equal unity. The depth to the bottom of the uppermost layer is found by superposition of Roman's (1934) master curves or of the analogous two-layer curves in the Mooney-Wetzel (1956) set. The best fit is obtained by means of curve $I_1$ interpolated when $k=-0.8$ and $k=-0.9$, with a $k$ value of $-0.82$, where $k$ is the resistivity contrast factor. The resistivity of the second layer is $\rho_2=0.1\ \rho_1$. The thickness of the first layer $d_1$ is found from the indicator line of the master curve to equal two units.

In the next step, one must estimate the depth to the third layer. Generally, the point of minimum resistivity is related to change in lithology in the following manner: (a) If the gradient of the resistivity curve increases sharply beyond the

minimum, then the minimum point signifies change in rock types. (*b*) If the gradient left of the minimum is very steep, whereas the gradient to the right of the minimum point is not, then the bottom of the layer is to the left of the minimum. (c) If both left and right slopes are gentle, the bottom of the layer with which the minimum is associated is to the right of the minimum point.

Under these rules of thumb, the depth to the layer associated with the minimum (often bedrock) may be estimated and readjusted a number of times. The estimate of depth to the third layer in this example would be eight units

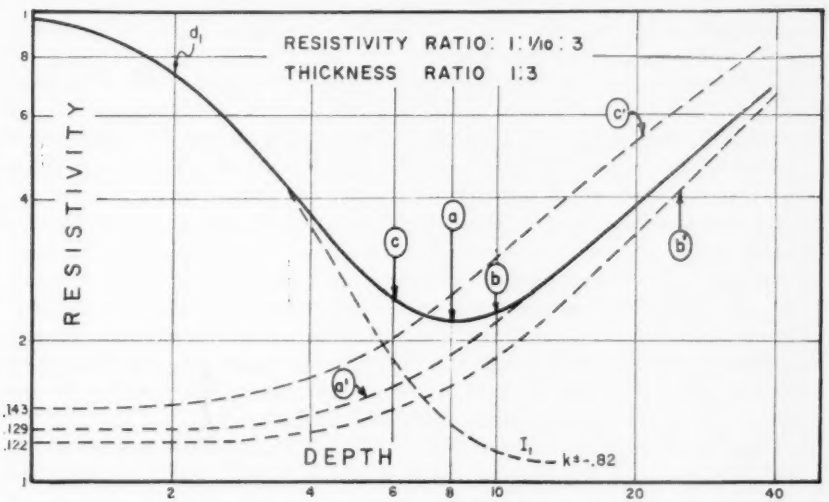


FIG. 3. Analysis of an ideal three-layer resistivity curve by means of the two-layer master curves.

(point *a*, Figure 3), indicating that the depth to the point of minimum resistivity equals the depth to the third layer in this particular case. We now know the resistivity of the upper two layers, the thickness of the top layer, and have an estimate of the thickness of the second layer. Substituting these in equation 1 above

$$\rho_{comp} = \frac{8}{\frac{2}{1} + \frac{6}{.1}} = .129$$

we obtain $\rho_{comp}$, the resistivity of the composite layer.

We now superimpose the two-layer master curves on the "field curve." to determine the resistivity of the third layer. However, the abscissa line $\rho = 1$ of the master curves must now coincide with the line $\rho = 0.129$ on the field curve,

and the ordinate depth indicator of the master curves must coincide with the vertical line intersecting the value "eight" on the field curve. It is found that only the master curve with a resistivity contrast factor $k=+0.92$ fits the field curve beyond the minimum point (curve $a'$, Figure 3). To obtain the resistivity of the third layer we substitute the obtained value of $k$ in equation (2). $\rho_3$ is found to equal 3.1, as compared with a value of 3 on the three layer master curve.

The self-corrective features of the method for fairly simple cases are demonstrated in the following examples: (a) Assume that the estimated depth to the third layer was incorrectly taken as 10 (point $b$, Figure 3). The ratio of thicknesses of the first to second layer are found as above, yielding depth values $d_1=2$, $d_2=8$. Substituting these into equation 1 we get $\rho=0.122$. Using 0.122 as the base of the abscissa of the master curves and 10 as the position of the vertical depth indicator of the master curves (point $b$), we find that the closest master curve fit is given by curve $b'$, although it does not coincide with the "field curve" even at large distances. Hence, this interpretation is not acceptable. (b) Assume now that the depth to the third layer was taken equal to six units. Then, $d_1=2$, $d_2=4$, and $\rho=0.143$ (from equation 1). Following the superposition procedure as above, curve $c'$ is found to give the best fit in this case, although it is far from satisfactory. By process of trial and error it is found that the curve $a'$, which was obtained from choosing the point $a$ as the bottom of the second layer, gives the most plausible fit, as required. This self-corrective feature makes it possible to obtain a better depth determination by this method than by recourse to either rules of thumb alone, or to ill-fitting three- or four-layer master curves. Analysis of two actual field curves further demonstrates the use of this method.

Sta. No. 6, Chariton County (Figure 4), is characterized by low resistivity contrasts and by a second layer which is about thirty times as thick as the top layer. By superimposing Roman's master curves on the shallow section of the curve, $h_1$, depth to the bottom of the first layer, is found to equal three ft. The depth to the third layer, $h_2$, is is found to be 100 ft, by a trial and error adjustment as above. By use of equation 1, the composite resistivity is found to equal 1.65. It is found that the master curve $k=0.7$ gives the best fit for the particular horizontal and vertical constraints. The depth to bedrock was found to be 116 ft in a hole drilled near the location of this station. It should be noted that although the second master curve does not fit closely the shallow points of the field curve, it approaches the deeper points asymptotically.

An analysis of a four-layer curve, using both two- and three-layer master curves, is illustrated by Figure 5. The shallow section of the curve is fitted with a three-layer Wetzel-McMurry curve ($I_1$). The master curve has a ratio of thicknesses $d_1:d_2::1:4$ and a resistivity ratio $1:1/10:1/3$. Hence, $d_1=1.45$ ft, $d_2=5.85$ ft and the composite resistivity of the top two layers is $\rho_{comp}=0.903$ kilohm-cm. $\rho_{comp}$ is now used as the abscissa of the two-layer master curves, which fit the field curve to a depth of about 30 ft (curve $I_2$, Figure 5), when $k=0.37$. The top three layers are combined to give a new composite resistivity value of 2.175.

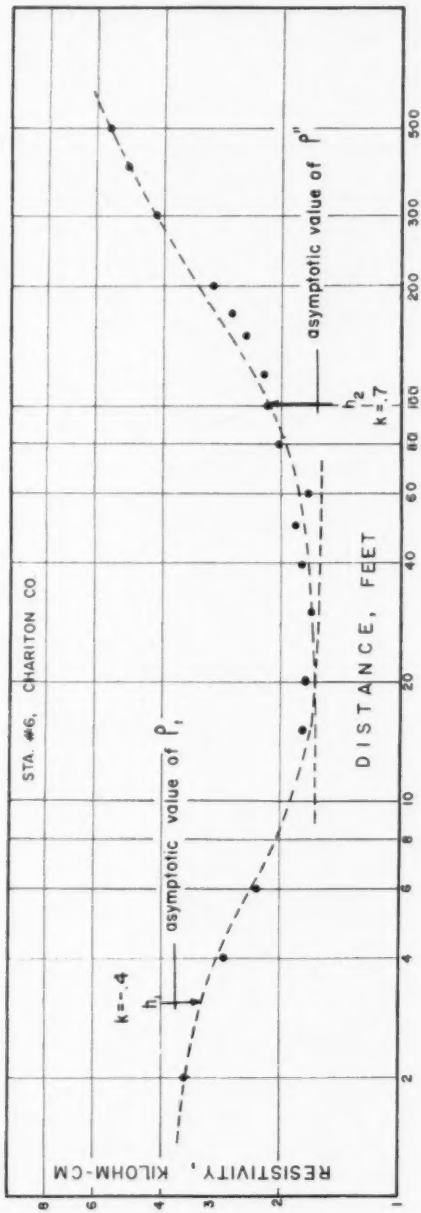


FIG. 4. Analysis of an actual three-layer field curve.

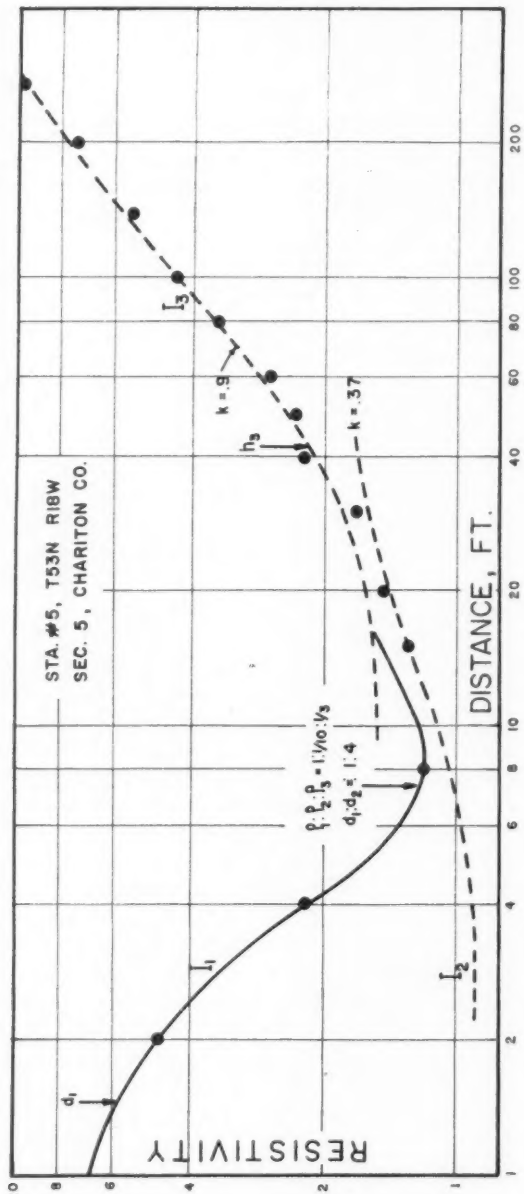


FIG. 5. Analysis of a four-layer field curve.

The best estimate of the depth to the fourth layer, $h_3$, is found to be 42 ft, and $k$ is found to equal 0.9 (curve $I_3$).

## RESULTS OF THE STUDY

Results of the quantitative study are given in a series of histograms showing the distribution of resistivities of (1) clay, (2) sand and gravel, and (3) bedrock, in Carroll and Chariton Counties (Figures 6 and 7). An exponential class interval of $\log_{1.7}$ of the resistivity in kilohm-cm was selected. The exponential scale was chosen because detectability of a deeper layer depends on a logarithmic change of resistivity. The base, which determines the class interval, was selected

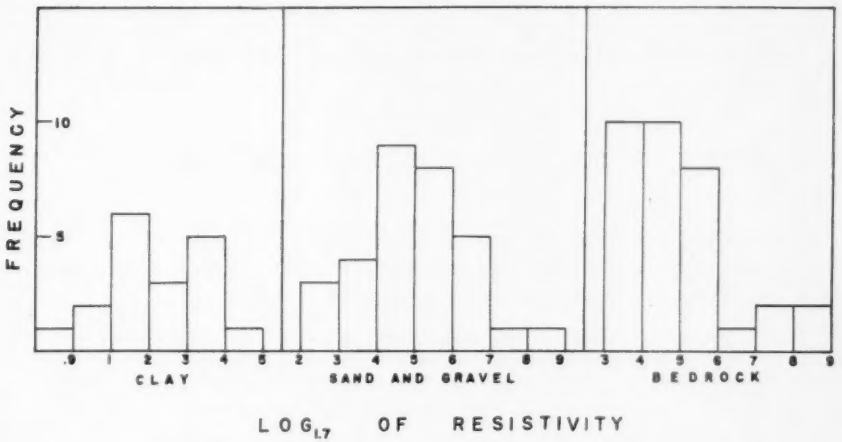


FIG. 6. Histograms of clay, sand-and-gravel and bedrock resistivity distribution in Carroll County, Mo. The abscissa is the $\log_{1.7}$ of the resistivity in kilohm-cm. The ordinate shows the number of samples in each class interval.

empirically so that a normal distribution curve could be obtained. The formula for change of base employed here is

$$\log_b H = \log_a N \log_b a. \tag{3}$$

In this case

$$y = \log_{1.7} x = \frac{\log_{10} x}{\log_{10} 1.7}, \tag{4}$$

where $y$ is the $\log_{1.7}$ of the resistivity of the class interval. Arbitrary class interval values increasing from 0.6 to 1.0 in increments of 0.1 and from one to ten in increments of one were selected. Equation 4 was solved for $x$, the resistivity in kilohm-cm of the class interval, for every value of $y$. A conversion table from

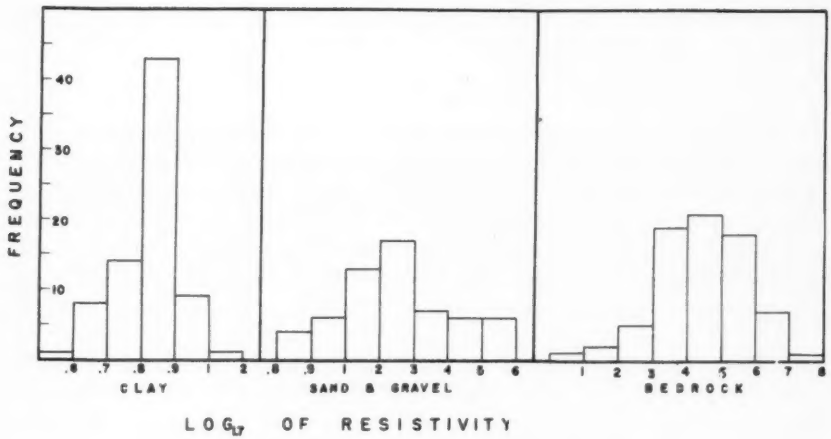


FIG. 7. Histograms of clay, sand-and-gravel and bedrock resistivity distribution in Chariton County, Mo.

$y$ to $x$ values is furnished in Table 1. The section of the histograms containing the interval $y=0.6$ to $y=1.0$ was expanded on the histograms to avoid compression of the left hand part of the distribution curve.

TABLE 1. CONVERSION TABLE FROM $x$, THE RESISTIVITY IN KILOHM-CM OF THE CLASS INTERVAL TO $y$, $\log_{1.7}$ OF THE RESISTIVITY IN KILOHM-CM

| $y$ | $x$ |
|---|---|
| .6 | 0.241 |
| .7 | 0.410 |
| .8 | 0.697 |
| .9 | 1.185 |
| 1.0 | 1.70 |
| 2.0 | 2.89 |
| 3.0 | 4.91 |
| 4.0 | 8.35 |
| 5.0 | 14.2 |
| 6.0 | 24.1 |
| 7.0 | 41.0 |
| 8.0 | 69.7 |
| 9.0 | 118.5 |
| 10.0 | 202.0 |

The high degree of overlap of the distribution curves in both counties indicates that little confidence could be placed in a numerical resistivity value as a means of separating bedrock from sand or gravel (Figures 8 and 9). These histograms indicate that it is possible to distinguish with greater certainty between layers of clay and layers of sand than between sand-and-gravel layers and bedrock.

Figure 10 shows the result of combining the distribution curves of each sam-

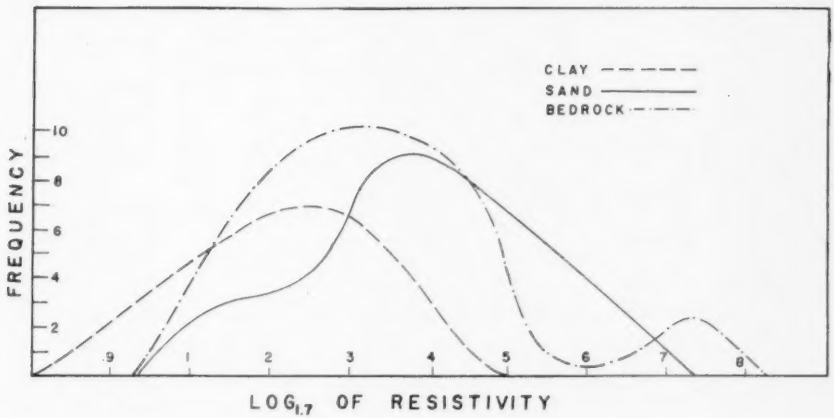


FIG. 8. Smoothed distribution curves of clay, sand-and-gravel and bedrock in Carroll County, Mo.

ple type of both counties. The figure indicates that no reliable distinction may be made among the three components, because the probability of error when the determination is made on a purely quantitative basis is too high for most purposes The wide degree of overlap of the resistivities of the different materials is partly due to the fact that the means and the modes of the electrical resistivity of each material varied considerably from one county to the other, as shown in Table 2.

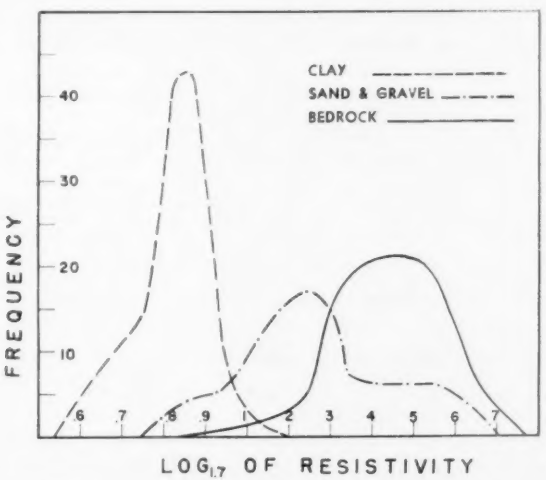


FIG. 9. Smoothed distribution curves of clay, sand-and-gravel and bedrock in Chariton County, Mo.

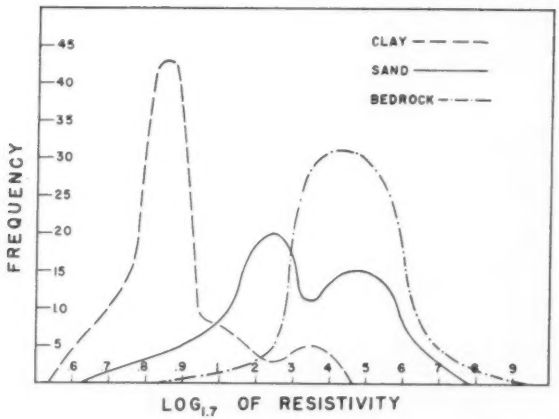


FIG. 10. Combined distribution curves of clay, sand-and-gravel and bedrock, Carroll and Chariton Counties, Mo. Note the overlap of the curves.

## QUALITATIVE APPROACH

Examination of the analysis above may lead the reader to conclude that the electrical resistivity method is ineffective in northern Missouri, inasmuch as there are no characteristic properties by which bedrock may be distinguished at every point from the overlying glacial drift. Such a conclusion is not completely warranted. It is true that lack of characteristic electrical properties of bedrock and the overlying drift will render a purely quantitative approach useless, yet it is possible to distinguish bedrock empirically by means of continuous extension

TABLE 2. MEAN RESISTIVITIES OF GLACIAL DRIFT AND BEDROCK IN CHARITON AND CARROLL COUNTIES

Mean bedrock resistivity in Carroll County is smaller than that of the overlying sand and gravel. Numbers are rounded out to two significant figures.

| County | | Resistivities in Kilohm-cm | | |
|---|---|---|---|---|
| | | Clay | Sand | Bedrock |
| Chariton | Mean resistivity | .80 | 8.10 | 16.0 |
| | No. of determinations | 52 | 57 | 72 |
| Carroll | Mean resistivity | 1.5 | 16.1 | 15.0 |
| | No. of determinations | 29 | 71 | 83 |
| Mean of both counties | | 1.06 | 12.6 | 15.5 |
| Deviation from the mean, percent | | | | |
| Chariton | | −24.5 | −35.5 | + 3.2 |
| Carroll | | +43.8 | +28.8 | − 2.2 |

of stations from a locality where lithology is known to the point of interest. Such a procedure, if workable, will be independent of the absolute resistivities of bedrock and drift, and will depend only on the lithological continuity in the area. The reliability of such a method will be related to the density of the correlation stations and the traceability of the electrical changes in the lithology between them. The results of the investigation described below tend to confirm the usefulness of the empirical method. An outstanding example of good depth determination by correlation is given below in the discussion of Figure 2, Grundy County.

*Grundy County*

Prior to the initiation of the resistivity the Missouri State Geological Survey published a general bedrock topography map based on logs obtained during the drilling program (Figure 11). One purpose of the electrical resistivity investigation was to determine the exact location at which the subsurface channel that enters the county in the northeast corner crossed Highway 65. This was accomplished by establishing an initial line of eleven stations at half-mile intervals between Tindall and Spickard. Although the channel was not found when a grid of one-half mile was employed, a one-quarter mile spacing yielded unmistakable evidence for the presence of the channel one mile south of Spickard. The interpreted depth to the deepest part of the channel was more than 200 ft (Figure 2). This depth was much greater than the depth to bedrock from the bedrock contour map of the Missouri Geological Survey (1956) which was based on drilling alone (Figure 11). To check this interpretation, the Missouri Geological Survey drilled at the approximate location of the channel. The drilling verified the predicted channel location. Another channel crossing, possibly a tributary of the channel encountered south of Spickard, was discovered by electrical resistivity about one-half mile west of Spickard and was subsequently verified by drilling north of Spickard, in Mercer County. As a result of the findings from the resistivity survey and of confirmatory drilling south of Spickard, the Missouri Geological Survey revised its bedrock topography map of Grundy County (Figure 12).

*Chariton County*

A reconnaissance resistivity survey of Chariton County was conducted before test drilling and without any reliable correlation wells. The purpose of the test was to determine the limitations of the resistivity method under conditions of very poor control. The contour map constructed on the basis of these observations compared satisfactorily with the bedrock topography map prepared from subsequent drilling data. The drill holes, which were closely spaced, afforded a more detailed contouring. The agreement between the two surveys is unexpected in view of the overlap of the resistivities of bedrock and glacial drift in this county. The general agreement is a result of the particular interpretive procedure: where-

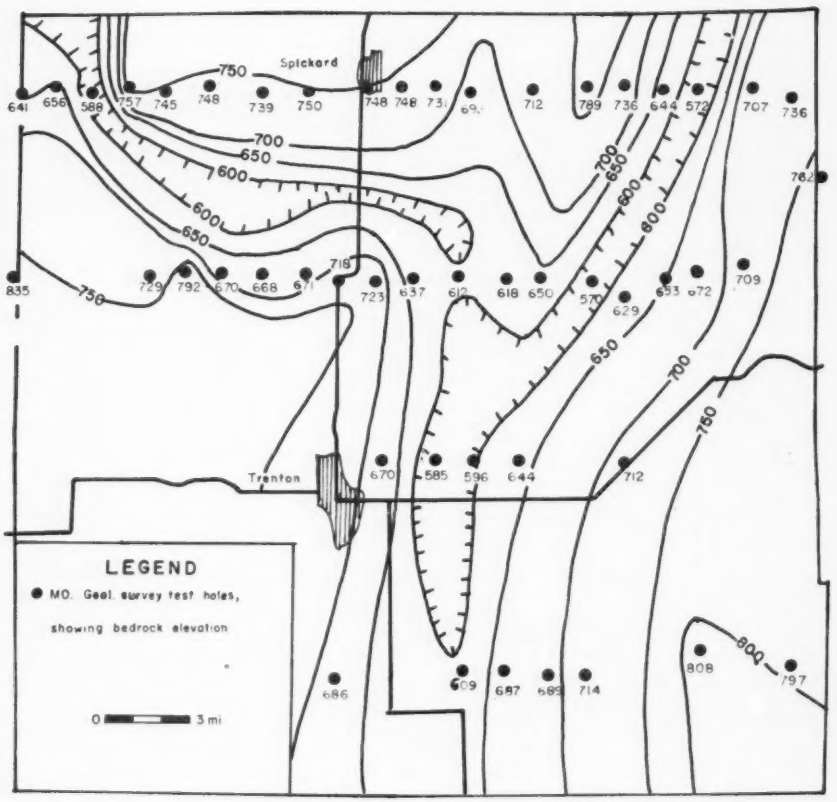


FIG. 11. Bedrock contour map based on drilling alone, Grundy County, Missouri (after D. L. Fuller and W. B. Russell).

ever possible, resistivity records were correlated with nearby drill holes; whenever the test records showed a distinctly different character from those of the correlation station, intermediate stations were established to trace out the change, thus reducing dependence on quantitative techniques which yielded ambiguous results in that county.

*Carroll County*

The purpose of the test in Carroll County was to determine to what extent the reliability of the geophysical method was enhanced by comparison of the resistivity curves with test well logs which were available during the study, and how far from such control could observations be safely taken.

The result of comparison of twelve resistivity stations with adjacent test holes which were not available during the study is presented in Table 3. The table suggests that the resistivity method is satisfactory in distinguishing between clay and sand, in spite of the overlap of the distribution curves. The table also suggests that there is only a small difference between the resistivity distribution of sand and gravel, on one hand, and bedrock on the other, indicating that quantitative techniques of bedrock determination will be of little use in that county. It should be noted that 50 percent of the predictions were correct in spite of poor resistivity contrasts. It should also be noted that most of the poor predictions were more than five miles away from the last correlation well.

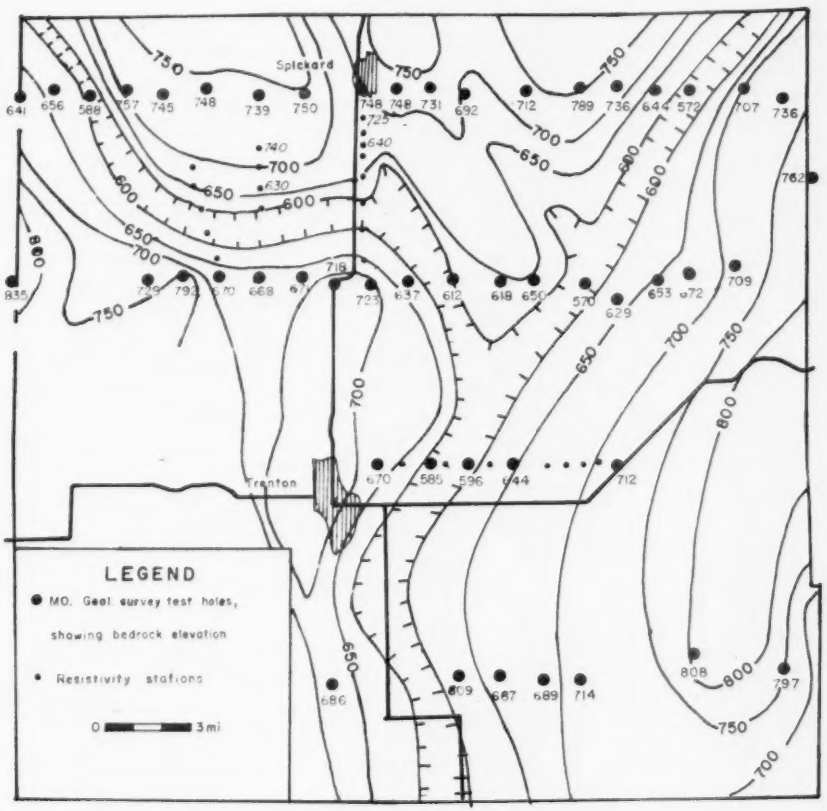


FIG. 12. Bedrock contour map based on drilling and resistivity, Grundy County, Missouri (after D. L. Fuller and W. B. Russell).

TABLE 3. COMPARISON OF PREDICTION FOR RESISTIVITY STATIONS WITH LOGS OF DRILL HOLES IN THEIR VICINITY, CARROLL COUNTY

D.H. refers to drill holes of the Missouri Geological Survey. Sta. refers to resistivity stations.

| | Soil and Clay, Ft | Sand and Gravel, Ft | Bedrock, Ft | Remarks |
|---|---|---|---|---|
| Sta. 57 | 0–22 | 22–68 | 68 | 450 ft S. of D.H. 833 |
| D.H. 833 | 0–38 | 38–135 | 135 | |
| Sta. 58 | 0–36<br>60–80 | 36– 60 | 80 | 400 ft W. of D.H. 834 |
| Sta. 58.1 | 0–14<br>52–78 | 14– 52 | 78 | 700 ft W. of D.H. 834 |
| D.H. 834 | 0–48<br>68–84 | 48– 68 | 84 | |
| Sta. 59 | 0–26 | 26– 50 | 50 | 300 ft S. of D.H. 836 |
| D.H. 836 | 0–25 | 25– 75 | 75 | |
| Sta. 60 | 0–18<br>26–57 | 18– 26 | 57 | 500 ft W. of D.H. 837 |
| D.H. 837 | 0–26 | 26– 96 | 96 | |
| Sta. 61 | 0– 8 | 8– 70 | 70 | 600 ft W. of D.H. 839 |
| D.H. 839 | 0– 5 | 5– 97 | 97 | |
| Sta. 63 | 0–10 | 10– 68 | 68 | 150 ft N. of D.H. 840 |
| D.H. 840 | 0–10 | 10– 82 | 82 | |
| Sta. 65 | 0– 4<br>32–70 | 4– 32 | 70 | At D.H. 842 |
| D.H. 842 | 0–10 | 10– 70 | 70 | |
| Sta. 45 | 0–20<br>55–75 | 20– 55<br>75–115 | 75 (?) | 500 ft S.E. of D.H. 847 |
| D.H. 847 | 0–20<br>55–75 | 75–135 | 135 | |
| Sta. 47 | 0–11 | 11– 46 | 46 | 700 ft E. of D.H. 846 |
| D.H. 846 | 0–15 | | 15 | |
| Sta. 43 | — | — | 60 | 500 ft N. of D.H. 848 |
| D.H. 848 | — | — | 80 | |
| Sta. 48 | 0–20<br>38–50 | | 20<br>50 | D.H. 849 is at elevation 20′ lower than station. Sta. is 650 ft N. of D.H. 849 |
| D.H. 849 | 0–20 | | 20 | |
| Sta. 50 | 0–22 | 22– 35 | 35 | 300 ft from D.H. 850 |
| D.H. 850 | 0–20 | 20– 45 | 45 | |

## CONCLUSIONS

Resistivity values obtained in northern Missouri for a particular type of rock varied considerably from one locality to another. Therefore, depth-to-bedrock could not be reliably determined by means of quantitative interpretation techniques alone.

On the other hand, the reliability of the resistivity method may be satisfactory wherever continuous, traceable changes of resistivity take place; it increases with closeness to reliable control and traceability of resistivity changes, and decreases with the lack of these conditions.

## ACKNOWLEDGMENTS

The author is indebted to Dr. James Brice for suggesting the project and for allocating part of the funds for carrying out this study from a National Science Foundation grant made to him for a study of the Pleistocene deposits of northern Missouri. The project was later concluded under the auspices of the Missouri State Geological Survey. The author is also indebted to Dr. Leroy Scharon of Washington University and Dr. Thomas Beveridge, State Geologist, Missouri State Geological Society.

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1094–1099, 3 FIGS.

# A NOTE ON CHEMICAL MAGNETIZATION OF ROCKS*

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AND E. H. STATHAM†

## ABSTRACT

Previously obtained magnetic data for Silurian samples from Alabama are presented. Both the remanent vector and the plane of maximum susceptibility lie close to the bedding plane for this ore containing chemically formed hematite. Now, X-ray measurements show preferred crystal orientation of the hematite in agreement with the susceptibility anisotropy. On the other hand, samples from the Tertiary in Texas containing hematite resulting from chemical alteration show no appreciable preferred crystal orientation or susceptibility anisotropy. Thus, in this case there is no obvious relationship between the crystal growth of the hematite and the direction of the earth's magnetic field. It is suggested that stresses probably played a role in the crystal orientation in the Silurian iron ore. An interesting chemical magnetization took place in the Weches of Tertiary age in Texas. The unaltered glauconite in the Weches is reversely magnetized whereas the limonite derived from the glauconite by weathering is normally magnetized.

## INTRODUCTION

We have been interested in the magnetization which occurs in the chemical deposition or chemical alteration of sediments (1956, 1957, 1958). We have pointed out the important role of hematite in chemical deposits and its interesting magnetic properties relative to its crystalline structure. At ordinary temperatures hematite is ferromagnetic in the basal plane and paramagnetic or slightly ferromagnetic along the ternary axis.

## SILURIAN IN ALABAMA

In a preceding paper (1958), measurements of both remanent magnetism and anisotropy of magnetic susceptibility were presented as made with samples of Clinton iron ore of Silurian age obtained near Birmingham, Alabama. These samples contain chemically formed hematite. The data are again presented in Figure 1, which shows the remanent north-seeking vectors plotted as circles on the lower hemisphere of a Schmidt net. The solid lines are traces of the planes of maximum susceptibility, the arrows coupling the remanent vector to the trace for the same sample. Since the planes of maximum susceptibility are very close to the bedding plane, we were not able to surmise whether this anisotropy is due to bedding geometry or to crystal orientation.

However, we now have X-ray data obtained by A. D. Kaiser, Jr. of the Geochemical Group in this laboratory. Intensity measurements were made by means of a Geiger counter with diffracted X-rays from an iron-target tube. Three slabs were cut from each of two samples: one slab approximately parallel to the bedding plane; one, in a perpendicular plane along strike; and one, in a perpendicular plane along dip. Data for three X-ray peaks are presented corresponding

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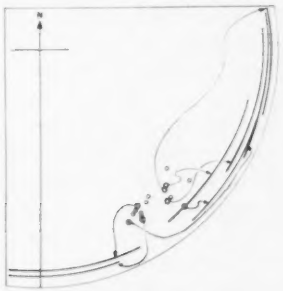

FIG. 1. Lower hemisphere plot of magnetic vectors and traces of planes of maximum susceptibility for Clinton iron ore.

to reflections from the crystal planes (110), (211), and ($1\bar{1}0$). The ($1\bar{1}0$) plane is perpendicular to the basal plane; unfortunately, the basal plane does not produce an X-ray reflection. The peak intensities in the case of each flat sample are given relative to the (211) peak.

Of the three planes, the (211) makes the smallest angle (about 38°) with the basal plane. In looking at the relative intensities of the peaks it will be noted that there is a decided difference for the bedding plane sections and the perpendicular-to-bedding sections. Although the weak (110) peak gives evidence of crystal orientation, we shall confine our attention to the two stronger peaks. As we shall see later in a sample showing no significant crystal orientation, the relative value of the ($1\bar{1}0$) peak varies from about 0.6 to 0.8. Therefore, the values of the ($1\bar{1}0$) peak in Table I are near normal in the case of the bedding plane sections but are abnormal and high for the perpendicular-to-bedding samples. Thus, there seems to be a preferred orientation of the ($1\bar{1}0$) planes in the perpendicular-to-bedding sections. Since the basal plane is perpendicular to these ($1\bar{1}0$) planes, it would appear to have a preferred orientation in the bedding plane. This orientation may explain at least in part the maximum magnetic

TABLE I

| Reflecting Planes and Spacings | Relative Peak Heights | | |
|---|---|---|---|
| | (110) 3.68A° | (211) 2.69A° | ($1\bar{1}0$) 2.51A° |
| Sample A | | | |
| Normal-to-Bedding Section Along Strike | .52 | 1.00 | 1.33 |
| Normal-to-Bedding Section Along Dip | .51 | 1.00 | 1.36 |
| Bedding Section | .33 | 1.00 | .67 |
| Sample F | | | |
| Normal-to-Bedding Section Along Strike | .45 | 1.00 | 1.07 |
| Normal-to-Bedding Section Along Dip | .53 | 1.00 | 1.28 |
| Bedding Section | .28 | 1.00 | .60 |

susceptibility occurring near the bedding plane; it will be remembered that for single crystals of hematite, maximum susceptibility is found in the basal plane.

Now, since the X-ray measurements do indicate a preferred crystal orientation, we come back to the question of whether the orientation was brought about by the magnetic field at the time of the chemical growth of the hematite or whether the orientation was due to stresses as evidenced by the near coincidence of the basal plane in the bedding plane. We still raise questions as to whether the remanent vector has been moved towards the plane of crystal orientation; whether the chemical growth of hematite took place later than Silurian time; or, perhaps, whether we have sampled inadequately. It will be recalled that the pole location computed from the remanent vector data seems to correspond to a time later than Silurian since the remanent vector is closer to the horizontal than would be expected. These are questions which we can not answer satisfactorily although we will discuss the crystal orientation problem later.

## TERTIARY IN TEXAS

We have investigated another unit containing hematite, a product of chemical alteration. In this case samples were obtained from large concretions and concretionary lenses, probably originally siderite, which occur in the Wilcox of lower Eocene age. Five samples were obtained from three locations covering a distance of about a half mile in a brick quarry to the east of Austin, Texas (Elgin Standard Brick & Tile Manufacturing Company). Figure 2 shows a Schmidt net on which

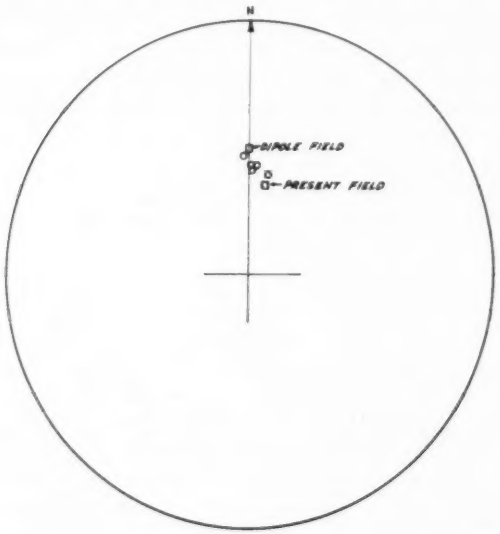


FIG. 2. Lower hemisphere plot of magnetic vectors for chemically altered samples of Wilcox.

are plotted the remanent vectors in the lower hemisphere. Each circle represents an average from two plugs. The direction of magnetization for a centered dipole along the earth's axis is indicated, as well as the direction of the present earth's field. The magnetization of the samples appears to be intermediate between the directions of the dipole field and the present field. This is not surprising since the chemical alteration probably took place in recent times.

In addition to these data, measurements were made of magnetic susceptibility by means of a modified Maxwell inductance bridge, which allows determinations to be made in any direction in the specimen. Plugs from four samples were measured. The susceptibility for these ranged from 6 to $9\times10^{-5}$ cgs units per cc. On the other hand, the remanence ranged from 5 to $16\times10^{-4}$ cgs units per cc. Thus, we obtain values of $Q$ from about 10 to about 40, the value of $Q$ being the ratio of the remanent magnetization to that induced in the earth's field (0.5 oersted). These values of $Q$ are extremely high for sediments. As to anisotropy of susceptibility, in no sample did the susceptibility vary by more than about one percent. Thus, compared with the Clinton ore, which showed variations of the order of 5 percent, these samples possess very little magnetic anisotropy.

The susceptibility measurements were also corroborated by X-ray measurements. Slabs were again cut from two samples: one slab being a N-S vertical section; one, a horizontal section; and one, roughly perpendicular to the magnetic vector. In this case a copper-target X-ray tube was used. In the following table the relative intensities of the (211) and ($1\bar{1}0$) peaks are given:

TABLE II

| | Relative Peak Heights | |
|---|---|---|
| | (211) | ($1\bar{1}0$) |
| Sample 2A | | |
| Vertical N-S Section | 1.00 | .71 |
| Horizontal Section | 1.00 | .80 |
| Section Dipping 35° to S | 1.00 | .81 |
| Sample 3A | | |
| Vertical N-S Section | 1.00 | .73 |
| Horizontal Section | 1.00 | .81 |
| Section Dipping 35° to S | 1.00 | .63 |

In no case was the ($1\bar{1}0$) peak stronger than the (211) peak. Thus, whereas the chemically formed hematite of the Clinton ore exhibits crystal orientation along with susceptibility anisotropy, the weathered Eocene exhibits no preferred crystal orientation or susceptibility anisotropy to any marked degree. Thus, it seems hematite particles can grow chemically and become magnetized without crystal orientation. This may be an example of the process suggested by Haigh (1957) in which the chemically formed particles become magnetized in the earth's field when they are very small and the relaxation time of magnetization is very

short. As the particles grow, the relaxation time becomes longer and the magnetization becomes frozen in.

On the other hand, we might suspect that stresses may have been responsible for the preferred crystal orientation in the Clinton iron ore which is an older rock and was probably subjected to higher stresses than were the Tertiary rocks in which the hematite was formed near the surface. We had previously found strong magnetic susceptibilities along the plane of foliation in some metamorphic rocks (1958); now, Hargraves (1959) has demonstrated preferred crystal orientation agreeing with a strong susceptibility anisotropy in metamorphic rocks bearing hemo-ilmenite. Although it is not suggested that the Clinton iron ore is metamorphosed, it may have been subjected to stresses on a much smaller scale.

The Weches formation of Eocene age furnishes a very interesting example of chemical magnetization. The unweathered glauconite of the Weches is reversely magnetized, whereas the weathered zone containing limonite derived from the glauconite is normally magnetized, the magnetization taking place in the recent earth's field as the limonite was chemically formed. Eleven samples of weathered Weches from seven locations were obtained in the counties of Anderson, Cherokee, and Smith in East Texas. These samples of unweathered glauconite were obtained from two locations in Cherokee and Nacogdoches Counties in East Texas. Figure 3 shows a Schmidt projection on which are plotted the remanent vectors, the dipole field direction, and the present earth's field direction. The

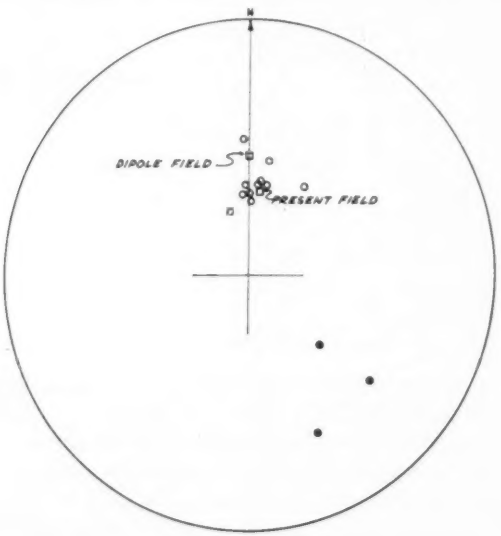


FIG. 3. Upper hemisphere (solid dots) and lower hemisphere (open circles and squares) plot of magnetic vectors for unweathered and weathered samples of Weches, respectively.

open circles are plotted on the lower hemisphere and represent the directions of magnetization of the weathered Weches. On the other hand, the solid dots represent the directions of magnetization on the upper hemisphere of the unweathered Weches glauconite. Again, the chemical magnetization seems to take a direction intermediate between that of the dipole field and that of the present field. This seems to be a clear case in which the chemical magnetization has actually reversed the original magnetization.

## CONCLUSION

We have presented two cases of chemically magnetized hematite, one case showing preferred crystalline orientation and magnetic susceptibility anisotropy, and the other showing neither property. There is a strong possibility that stresses played a role in one case and not in the other. We have also presented a case in which the chemical magnetization has reversed the original magnetization of the sediment.

## ACKNOWLEDGMENT

We would like to acknowledge the help of P. H. Monaghan in making some early X-ray measurements.

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GEOPHYSICS, VOL. XXV, NO. 5 (OCTOBER, 1960), PP. 1100–1118, 10 FIGS.

# GEOPHYSICAL ACTIVITY IN 1959*

HOMER G. PATRICK†

## THE PETROLEUM INDUSTRY

Geophysical activity by the petroleum industry in 1959 was reduced in all the major areas of the free world except in the Far East where a small over-all gain was reported. An average of 957 geophysical crews of all types operated in world-wide exploration during the year. In 1956, a record high year, the world-wide average was 1,136 crews.

References have been made in the literature concerning geophysical work in the Soviet Union and China. Following is a quotation from an article "The Present and Future of the Oil and Gas Industries of the USSR" by Prof. F. Trebin, Doctor of Technical Sciences and I. Zlotnikov, Engineer, which was published in the May 1960 issue of Independent Petroleum Association of America *Monthly:* "Especially widely employed are the seismic methods of prospecting (the reflected waves method, the correlated refracted waves method, focused logging, and so on). Today the USSR has 400 seismic teams prospecting for oil and gas and by 1965 there are to be 1,200." In an article from the November 1959 issue of *Izvestiya Academy of Science—Geophysics*, the authors make no direct statement about the number of crews involved but they mention geophysical work, particularly reflection and refraction seismic work in the following widely separated areas: The Tsaidam Depression, Yumning Area, which lies in approximately 40° N. latitude and 97° E. longitude and is separated from the Tsaidam Depression by a high mountain range (Nan-Shan), Province of Szechwan in the vicinity of Chengtu (31° N., 104° E.), and North China Plain in the vicinity of Chenghcow in the north and Nanking in the south.

Table I shows the distribution of world-wide geophysics exploration in 1959 according to area and to method. Corresponding figures for 1958 and rate comparisons with the previous year's activities are also shown. Over-all activity in the United States was only slightly below the 1958 level. Canada reported a 25.6 percent reduction in the use of geophysics while in the Western Hemisphere, as a whole, the 1959 activity was down by 5.1 percent compared to 1958. A greater reduction took place in the Eastern Hemisphere where 1959 activity was reduced 14.5 percent. World-wide activity in geophysics exploration declined 8.9 percent in 1959.

* Report of the Committee on Geophysical Activity of the Society of Exploration Geophysicists. The members of the Committee are: Kenneth L. Cook, R. J. Copeland, Santos Figueroa Huerta, Herbert Hoover, Jr., C. N. Hurry, Kumiji Iida, Bart W. Sorge, L. R. Tucker and Homer G. Patrick, Chairman.

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TABLE I

CREW-MONTHS OF GEOPHYSICAL EXPLORATION FOR PETROLEUM—1959

| | U.S.A. | | | Canada | | | Western Hemisphere | | | Eastern Hemisphere | | | World | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1958 | 1959 | Percent Change | 1958 | 1959 | Percent Change | 1958 | 1959 | Percent Change | 1958 | 1959 | Percent Change | 1958 | 1959 | Percent Change |
| Seismic | 5,064 | 5,097 | + 0.65 | 1,065 | 796 | −25.3 | 7,249 | 6,988 | − 3.6 | 3,077 | 2,735 | −12.5 | 10,326 | 9,723 | − 5.8 |
| Gravity | 612 | 548 | −10.5 | 65 | 41 | −36.9 | 1,194 | 972 | −18.6 | 670 | 517 | −22.8 | 1,864 | 1,489 | −20.1 |
| Magnetic | 55 | 51 | − 7.3 | | 1 | + — | 102 | 52 | −49.0 | 124 | 109 | −12.1 | 226 | 161 | −28.8 |
| Other | | | | | 3 | + — | 2 | 3 | +50.0 | 183 | 105 | −42.6 | 185 | 108 | −41.6 |
| Total | 5,731 | 5,696 | − 0.61 | 1,130 | 841 | −25.6 | 8,547 | 8,015 | − 5.1 | 4,054 | 3,466 | −14.5 | 12,601 | 11,481 | − 8.9 |

Figure 1 shows the world distribution of seismograph prospecting during 1959. The percentage figures in the divisions and the sub-divisions of the chart represent the proportion of the world's seismograph work carried out in the areas shown. The (+) and (−) signs indicate whether the percentage figures shown are greater than or less than the corresponding figures for the previous year. The United States continues to be the scene of greatest seismograph activity, with 52.4 percent of the world's total effort during 1959. Seismic explorations in North America during the year amounted to 63.3 percent of the total. The division of seismic work between the two hemispheres was 71.9 percent in the Western Hemisphere and 28.1 percent in the Eastern Hemisphere. The major portion of the seismograph work in the Eastern Hemisphere was done in Europe

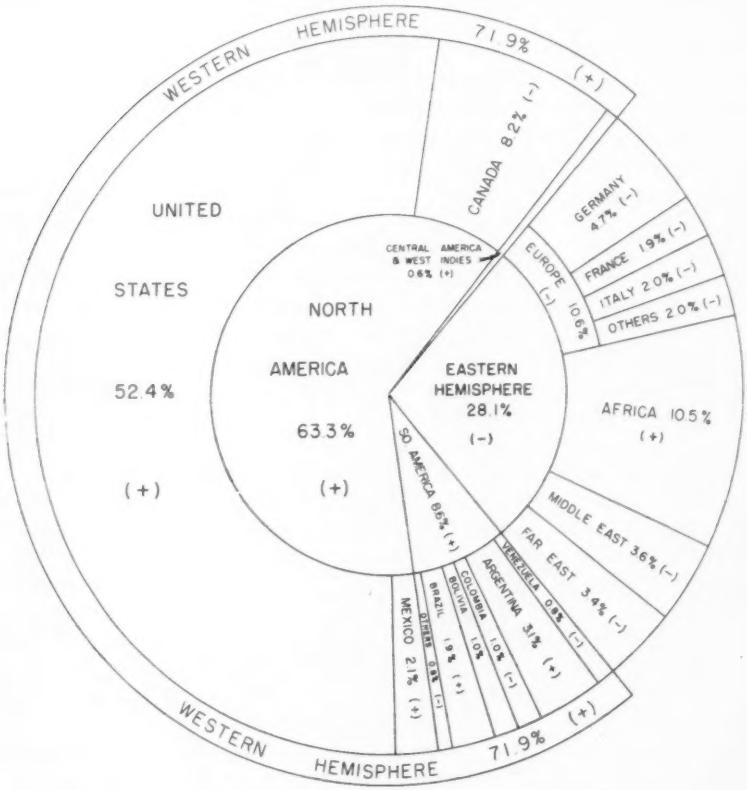


FIG. 1. World distribution of seismograph prospecting in 1959.

with 10.6 percent and in Africa with 10.5 percent of the world's total. The remainder of the seismic activity in the Eastern Hemisphere was about equally divided between the Middle East (3.6 percent) and the Far East (3.4 percent). World distribution of gravity prospecting in 1959 is shown in Figure 2. Gravity exploration work in the Western Hemisphere during the year amounted to 65.3 percent of the total, 43.7 percent in North America and 21.6 percent in South America. The greatest concentration of gravity work in the Eastern Hemisphere during the year was in the Far East where 13.3 percent of the world's total work was done. Africa accounted for 7.8 percent, the Middle East 7.7 percent and Europe 5.9 percent of the 1959 gravity explorations.

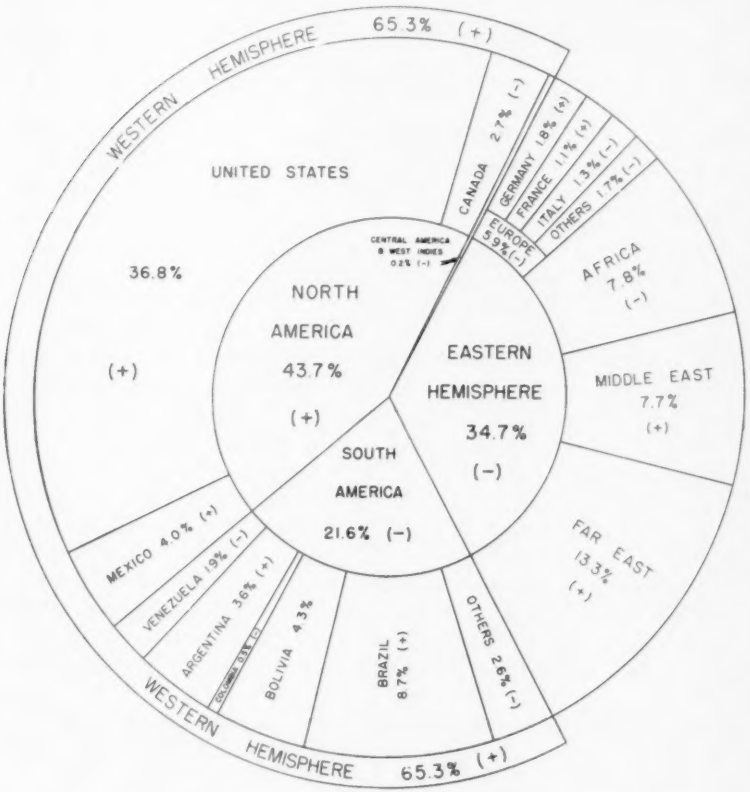


FIG. 2. World distribution of gravimeter prospecting in 1959.

EASTERN HEMISPHERE

*Europe*

GEOPHYSICAL CREW-MONTHS IN EUROPE—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Austria | 37 | 34 | 12 | | | | | 33 | 116 |
| France | 12 | 170 | | 16 | | 9 | | | 207 |
| Germany | 106 | 350 | | 27 | | | | 29 | 512 |
| Italy & Sicily | 79 | 116 | 12 | 8 | 1 | 2 | | 37 | 255 |
| Netherlands | 12 | 15 | | | | | | | 27 |
| Spain | 15 | 36 | | 13 | | | | | 64 |
| Switzerland | 5 | 12 | | | | | | | 17 |
| United Kingdom | 12 | 15 | | | | | | | 27 |
| | 278 | 748 | 24 | 64 | 1 | 11 | | 99 | 1,225 |
| Total | 1,026 | | 88 | | 12 | | 99 | | 1,225 |

A decline in the use of geophysical methods of all types was reported in Europe during 1959. Activity in seismic work was reduced to 1,026 crew-months compared to 1,417 crew-months in 1958 and 1,517 crew-months in 1957. Use of the gravity method was reduced to 88 crew-months and ground magnetic work amounted to only 12 crew-months during the year. West Germany was the leader in geophysical activity among the European nations in 1959. Geophysical exploration work in Germany was twice that reported in Italy, the second ranking country. France ranked third but total operations in that country were less than half that reported in 1958. Activity in Austria during 1959 was about equal to the 1958 activity. Other countries where some geophysical work was reported during the year are Netherlands, Spain, Switzerland and United Kingdom. Geophysical surveys other than seismic, gravity and ground magnetic which were reported included telluric current (2.1 crew-months) and electrical surveys (12 crew-months) in Austria; electromagnetic (1,712 line-miles) and airborne radiation detection surveys (2,687 line-miles) in England; airborne magnetometer (3,000 line-miles) and electrical surveys (9 crew-months) in France; airborne magnetometer (138 line-miles), geoelectric surveys (14 crew-months) and other types (15 crew-months) in Germany; airborne magnetometer (3,500 line-miles) and electrical surveys (37 crew-months) in Italy; electromagnetic (193 line-miles) in Spain and electromagnetic (367 line-miles) in Cyprus.

Contract geophysical companies did 73 percent of the seismic work, 73 percent of the gravity work and almost all of the work of other types carried out in Europe during 1959.

*Africa*

GEOPHYSICAL CREW-MONTHS IN AFRICA—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Algeria | 18 | 313 | | | | | | | 331 |
| Cabinda | | 12 | | | | | | | 12 |
| Egypt | 12 | 13 | | 12 | | | | | 37 |
| Fr. E & W Africa | 12 | 6 | | 1 | | | | | 19 |
| Gabron | 12 | 21 | | 7 | | | | | 40 |
| Libya | 48 | 264 | 12 | 20 | | 6 | | | 350 |
| Ivory Coast | | 8 | | | | | | | 8 |
| Madagascar | | 6 | | 5 | | | | | 11 |
| Morocco | 4 | 5 | 9 | | | | | | 18 |
| Mozambique | 24 | | | 22 | | 11 | | | 57 |
| Nigeria | 24 | 74 | | | | | | | 98 |
| Portugese Guinea | | 13 | | 24 | | | | | 37 |
| Senegal | 12 | 32 | | | | | | | 44 |
| Br. Somaliland | | 9 | | | | | | | 9 |
| It. Somaliland | | 4 | | | | | | | 4 |
| Tunisia | | 24 | | | | | | | 24 |
| Other | 24 | 25 | | 4 | | | | | 53 |
| | 190 | 829 | 21 | 95 | | 17 | | | 1,152 |
| Total | 1,019 | | 116 | | 17 | | | | 1,152 |

Geophysical exploration continued at a high level in the countries of Africa during 1959. Seismic work was increased from 829 crew-months in 1958 to 1,019 crew-months in 1959. Explorations by methods other than seismic were reduced during the year. Algeria and Libya continue to be leaders in geophysical activity among the nations of Africa, accounting for more than half of the total work on the continent. Nigeria ranked third, followed by Mozambique and Senegal. A number of aeromagnetic surveys were made by the petroleum industry in Africa in 1959. Those reported are as follows: 2,350 line-miles in South Africa, 6,940 line-miles in Southwest Africa, 17,000 line-miles in French Sahara, 1,100 line-miles in Angola, 5,809 line-miles in Belgian Congo, 8,000 line-miles in Morocco, 10,000 line-miles in Spanish Sahara and 2,250 line-miles in Somaliland. In addition an airborne radiation detection survey (975 line-miles) was carried out in Angola and an electromagnetic survey (1,240 line-miles) was made in Uganda.

Geophysical contractors did 81 percent of the seismic work, 82 percent of the gravity work and all geophysical work of other types in Africa during 1959.

*Middle East*

Geophysical activity in the Middle East declined during 1959 as a result of reduced seismic and magnetic work. Gravity meter exploration was increased by a small amount. Greatest activity in geophysical exploration was in Iran and Turkey with an equal amount in each country. Oman and Iraq ranked third and

GEOPHYSICAL CREW-MONTHS IN THE MIDDLE EAST—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Aden | | 3 | | 12 | | | | | 15 |
| Dhofar | | 24 | | | | | | | 24 |
| Israel | | 12 | | 2 | | | | 2 | 16 |
| Iran | 10 | 45 | 9 | 42 | | | | | 106 |
| Iraq | 12 | 63 | | | | | | | 75 |
| Saudi Arabia | | 31 | | | | | | | 31 |
| Turkey (Asian) | 24 | 57 | | 16 | | 8 | | | 105 |
| Syria | | 20 | | | | | | | 20 |
| Quatar | | 7 | | | | | | | 7 |
| Oman | | 39 | | 34 | | 12 | | | 85 |
| Lebanon | | 7 | | | | | | | 7 |
| Other | | 1 | | | | | | | 1 |
| | 46 | 309 | 9 | 106 | | 20 | | 2 | 492 |
| Total | 355 | | 115 | | 20 | | 2 | | 492 |

fourth in activity among the Middle East countries. An airborne magnetometer survey of 8,000 line-miles was carried out in Turkey during the year.

Contract companies did 87 percent of the seismic work, 92 percent of the gravity work and all the geophysical work by other methods in the Middle East during the year.

*Far East*

GEOPHYSICAL CREW-MONTHS IN FAR EAST—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Br. Borneo | | | | | | | | | |
| Burma | | 12 | | | | | | | 12 |
| India | | 46 | | 58 | | 58 | | | 162 |
| Indonesia | 3 | 42 | | 12 | | | | | 57 |
| Japan | 11 | 58 | 9 | 25 | | | | 4 | 107 |
| New Guinea | | 11 | | 7 | | | | | 18 |
| Pakistan | 16 | 50 | | 26 | | 2 | | | 94 |
| Philippines | | 23 | | 55 | | | | | 78 |
| Australia | | 23 | | 3 | | | | | 26 |
| Formosa | 20 | | 3 | | | | | | 23 |
| New Zealand | | 12 | | | | | | | 12 |
| Other | | 8 | | | | | | | 8 |
| | 50 | 285 | 12 | 186 | | 60 | | 4 | 597 |
| Total | 335 | | 198 | | 60 | | 4 | | 597 |

A slight decline in seismic work was more than offset by increased use of the gravity and magnetic methods in the countries of the Far East in 1959. As a result the over-all geophysical activity was greater than in 1958. India, Japan,

Pakistan and the Philippines were the scenes of greatest activity during the year.

Crews of contract geophysical companies did 85 percent of the seismic work, 94 percent of the gravity work and all the geophysical work of other types in the Far East during 1959.

WESTERN HEMISPHERE

*South America*

GEOPHYSICAL CREW-MONTHS IN SOUTH AMERICA—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Argentina | 244 | 58 | 53 | | | | | | 355 |
| Bolivia | 17 | 85 | 44 | 20 | | | | | 166 |
| Brazil | | 187 | 71 | 59 | | | | | 317 |
| British Guiana | | 1 | | | | | | | 1 |
| Chile | 24 | 24 | 12 | | | | | | 60 |
| Colombia | 35 | 64 | 8 | | | | | | 107 |
| Paraguay | | | | 1 | | | | | 1 |
| Peru | | 26 | 24 | | | | | | 50 |
| Venezuela | 25 | 48 | 12 | 17 | | | | | 102 |
| Other | | | | | | | | | |
| | 345 | 493 | 224 | 97 | | | | | 1,159 |
| Total | 838 | | 321 | | | | | | 1,159 |

Geophysical activity in the countries of South America during the year 1959 was less than in the previous year but was considerably above the 1957 level. Seismic work declined from 876 crew-months in 1958 to 838 crew-months in 1959. Total gravity work amounted to 404 crew-months in 1958 and 321 crew-months in 1959. Argentina, with 302 crew-months, was the scene of greatest seismic activity during 1959. Brazil ranked second with 187 crew-months followed by Bolivia with 102 crew-months. Venezuela with only 73 crew-months seismic work in 1959 dropped from first place in activity, a position usually held by that country. In gravity meter exploration work Brazil was the leader with 130 crew-months, Bolivia was second with 64 crew-months, followed by Argentina with 53 crew-months and Venezuela with 29 crew-months. Other countries in which a small amount of gravity work was reported are Chile, Colombia, Paraguay and Peru. Aeromagnetic surveys were carried out during the year in Argentina, Surinam and Venezuela. The work in Surinam amounted to 68,000 line-miles. In Venezuela 35,000 line-miles were reported and in Argentina 11,600 line-miles were flown covering an area of 6,500 square miles.

Contract geophysical companies did 59 percent of seismic work in South America in 1959 compared to 61 percent the previous year. Geophysical contractors operated only 30 percent of the gravity crews in the countries of South America in 1959. All aeromagnetic work was done by contract companies.

*Central America and the West Indies*

GEOPHYSICAL CREW-MONTHS IN CENTRAL AMERICA AND THE WEST INDIES—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Bahamas | | | | | | | | | |
| British Honduras | | 12 | | | | | | | 12 |
| Cuba | | 6 | | | | | | | 6 |
| Costa Rica | | 2 | | | | | | | 2 |
| Guatemala | | 27 | | 2 | | | | | 29 |
| Panama | | | | | | | | | |
| Trinidad | | 6 | | | | | | | 6 |
| Other | | | | | | | | | |
| | | 53 | | 2 | | | | | 55 |
| Total | 53 | | 2 | | | | | | 55 |

Reports of geophysical activity in the countries of Central America and the West Indies during the year showed an increase in seismic work over the previous year, and a marked decline in gravity surveys. The greatest activity in the area was in Guatemala where 27 crew-months seismic work and 2 crew-months gravity work were carried out. Seismic work was also done in British Honduras, Cuba, Costa Rica and Trinidad. All geophysical work reported in Central America and the West Indies during 1959 was done by contract geophysical companies.

NORTH AMERICA

*Mexico*

GEOPHYSICAL CREW-MONTHS IN MEXICO—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Mexico | 96 | 108 | 24 | 36 | | | | | 264 |
| Total | 204 | | 60 | | | | | | 264 |

Geophysical exploration by the petroleum industry in Mexico has remained about constant for the past several years. Total activity during 1959 was 204 crew-months seismic work and 60 crew-months gravity work. Geophysical contractors did 53 percent of the seismic work and 60 percent of the gravity work in Mexico during the year.

*Canada*

Geophysical activity by the petroleum industry in Canada during 1959 continued the downward trend which was started in the fall of 1952. Seismic work declined from 1,065 crew-months in 1958 to 796 crew-months in 1959, a reduc-

GEOPHYSICAL CREW-MONTHS IN CANADA—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Alberta | 226 | 323 | | 5 | | | | | 554 |
| Saskatchewan | 54 | 34 | | 1 | | | | | 89 |
| British Columbia | 25 | 96 | | 3 | | | | | 124 |
| N.W. Territories | 1 | 29 | 2 | 5 | | | | | 37 |
| Manitoba | 6 | | | | | | | | 6 |
| Ontario | | | | 15 | | | | 3 | 18 |
| Nova Scotia | | 2 | | 6 | | 1 | | | 9 |
| New Brunswick | | | | 4 | | | | | 4 |
| | 312 | 484 | 2 | 39 | | 1 | | 3 | 841 |
| Total | 796 | | 41 | | 1 | | 3 | | 841 |

tion of 25 percent. The total seismic effort in 1959 was only about half that of five years ago, 1954. Gravity exploration work was reduced to 41 crew-months during the year compared to 65 crew-months the previous year. Increased use of the aerial magnetometer in petroleum exploration was reported in 1959. A total of 66,625 line-miles were flown in aeromagnetic surveys during the year compared to 52,066 line-miles in 1958. Alberta continued to lead in seismic activity in 1959 with 549 crew-months followed by British Columbia with 121 crew-months, Saskatchewan with 88 crew-months and Northwest Territories with 30 crew-months. No large concentration of gravity work was reported during the year. Ontario was the leader with 15 crew-months. Northwest Territories with 7 crew-months, Nova Scotia with 6 crew-months, Alberta with 5 crew-months and New Brunswick with 4 crew-months were the scenes of limited gravity activity.

Monthly variations in seismograph and gravity meter crew-months in Canada for the years 1947 through 1959 are shown in Figure 3. As shown by the graph the greatest activity in seismic work in the year 1959 occurred during the months of January, February and March with a sharp reduction in April to 48 crews. Some crews were added during the following months but a decline to 43 crews in November brought Canadian seismic activity to its lowest point since 1948. Most of the gravity surveys reported in Canada during the year were carried out during the summer months.

The greatest concentration of aerial magnetometer work by the petroleum industry in 1959 was in the province of British Columbia where 56,465 line-miles were reported. Other aeromagnetic surveys were carried out in Nova Scotia, 4,500 line-miles; Alberta, 4,160 line-miles and Yukon, 1,500 line-miles.

The 1959 reduction of seismic activity in Canada was borne almost entirely by the contract geophysical companies. Contract companies lost 261 crew-months out of a total reduction of 269 crew-months. Contract companies did only 58 percent of the seismic work in 1959, compared to 70 percent in 1958 and 76 per-

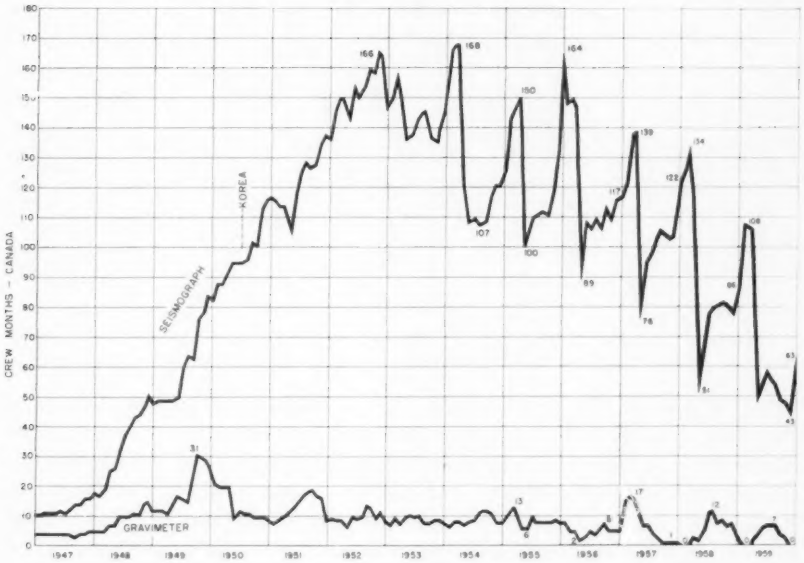


FIG. 3. Monthly variations in seismograph and gravimeter crew-months in Canada.

cent in 1957. As in the past years contractors did all of the aeromagnetic work and 95 percent of the gravity work in Canada during 1959.

*United States*

Recent years have been characterized by a downward trend in geophysical exploration by the petroleum industry in the United States. In 1959 a leveling off of activity was indicated. Total seismic work in the United States during the year was 5,097 crew-months, an increase of 33 crew-months over the previous year. Gravity meter exploration continued to decline and ground magnetic work was slightly less than in 1958. Aeromagnetic work was reduced from 121,396 line-miles in 1958 to 64,639 line-miles in 1959, a reduction of 46.7 percent. The decline in gravity and magnetic surveys, however, is not considered to be indicative of a continued downward trend in U. S. geophysical activity.

Figure 4 shows the monthly variations in seismic and gravity crew-months since 1944. Use of the seismograph was increased in the early part of 1959 after a low of 395 crews was reached in November 1958. The peak of the year's activity, 440 crews, was reached at mid-year. The low point in seismic activity again occurred in November when 397 crews were employed. An average of 46 gravity crews was in operation during the year, the range being from a low of 41 crews at the beginning of the year to 53 crews in late summer. Ground magnetic work declined from 55 crew-months in 1958 to 51 crew-months in 1959. A total of

GEOPHYSICAL CREW-MONTHS IN U.S.A.—1959

| | Seismic | | Gravity | | Magnetic | | Other | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Co. | Cont. | Co. | Cont. | Co. | Cont. | Co. | Cont. | |
| Texas | 692 | 1,019 | 67 | 82 | 12 | 16 | | | 1,888 |
| Louisiana | 379 | 550 | 35 | 33 | | | | | 997 |
| New Mexico | 183 | 140 | 42 | 34 | 12 | | | | 411 |
| California | 19 | 97 | | 20 | | | | | 136 |
| Wyoming | 173 | 127 | 1 | 21 | | | | | 322 |
| Colorado | 90 | 36 | 3 | 14 | | | | | 143 |
| Montana | 75 | 82 | 6 | 3 | | | | | 166 |
| Florida | 42 | | 3 | | | | | | 45 |
| Utah | 74 | 70 | | 18 | | | | | 162 |
| Oklahoma | 144 | 164 | | | | | | | 308 |
| North Dakota | 52 | 38 | | 5 | | | | | 95 |
| Mississippi | 234 | 203 | 33 | 21 | | | | | 491 |
| Kansas | 62 | 59 | 12 | | 11 | | | | 144 |
| Arkansas | 38 | 26 | | | | | | | 64 |
| Arizona | 2 | 24 | | | | | | | 26 |
| Alaska | 15 | 82 | 3 | 7 | | | | | 107 |
| Alabama | 6 | 21 | 15 | 5 | | | | | 47 |
| Other | 9 | 70 | 23 | 42 | | | | | 144 |
| | 2,289 | 2,808 | 243 | 305 | 35 | 16 | | | 5,696 |
| Total | 5,097 | | 548 | | 51 | | | | 5,696 |

FIG. 4. Monthly variations in seismograph and gravimeter crew-months in the U.S.A.

64,639 line-miles were flown in airborne magnetometer surveys in 1959 covering 85,750 square miles at an approximate cost of one-half million dollars. A breakdown of 1959 aeromagnetic work, according to states, is as follows: Arizona, 2,100 line-miles; California, 12,897 line-miles; Colorado, 3,400 line-miles; Georgia, 400 line-miles; Kentucky, 12,000 line-miles; Mississippi-Alabama, 13,000 line-miles; Texas, 6,542 line-miles; Utah, 10,000 line-miles; and Wyoming, 700 line-miles.

Figure 5 shows the distribution of seismograph prospecting in the U.S.A. in 1959. A slight reduction in seismic effort in Louisiana was offset by a corresponding gain in Texas so that the two states combined accounted for more than fifty percent of the total seismic work in the United States. Distribution of the work within the two states was about the same as in recent years. Some reduction in seismic work occurred in the Rocky Mountain states during the year but activity began to increase, particularly in Utah at the end of the year. Slight increases

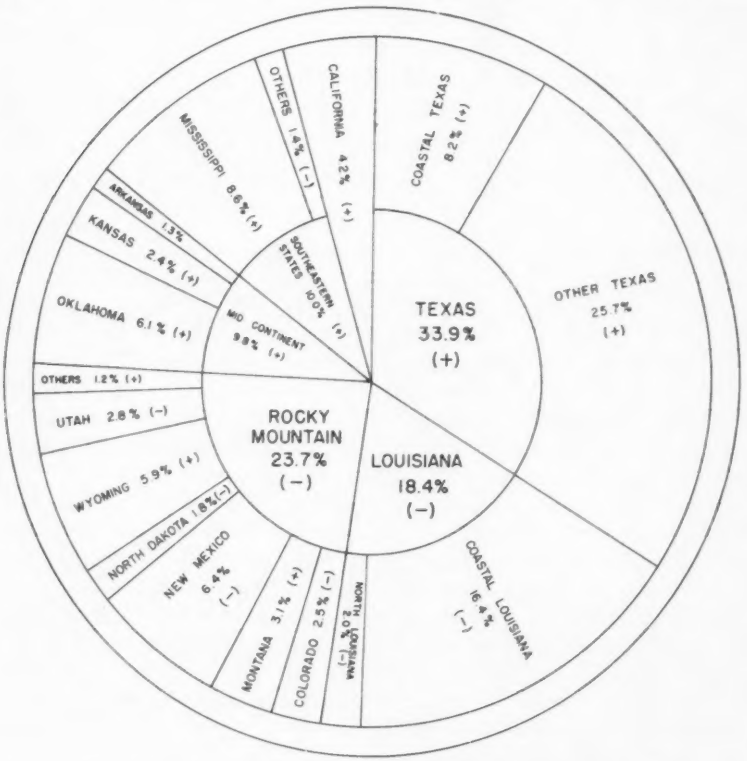


FIG. 5. Distribution of seismograph prospecting in the U.S.A. in 1959.

were reported in the Midcontinent and Southeastern states and in California.

The distribution of gravity exploration work in the U.S.A. in 1959 is shown in Figure 6. The Rocky Mountain states accounted for the greatest percentage of the total U. S. gravity work with 31.4 percent. Texas was second with 27.2 percent and Louisiana third with 12.4 percent of the total. Gravity exploration

FIG. 6. Distribution of gravimeter prospecting in the U.S.A. in 1959.

work increased percentagewise in the Midcontinent and Southeastern states but declined in the Pacific Coast states.

Figures 7 and 8 show by years the number of seismograph and gravimeter crew-months in the Gulf of Mexico off the coasts of Louisiana and Texas. Both seismic and gravity activity increased slightly in the Louisiana offshore area in 1959 as compared to the previous year. Operations in the Gulf of Mexico off the Texas coast amounted to 12 crew-months seismic work and 12 crew-months gravity work during the year.

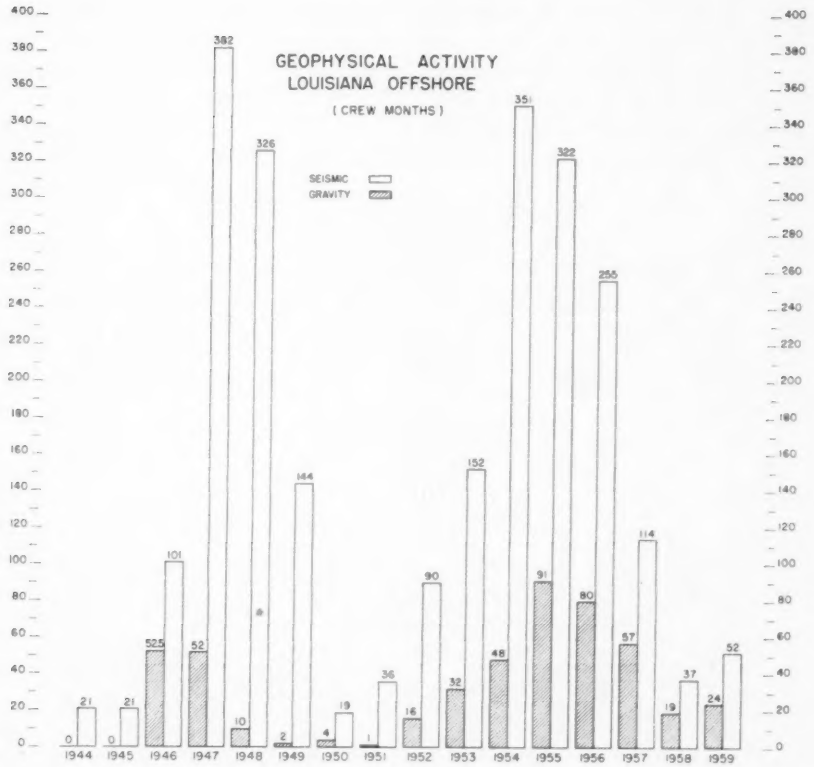


FIG. 7. Seismograph and gravimeter crew-months by years in the Louisiana portion of the Gulf of Mexico.

Contract geophysical companies did 55.1 percent of the seismic work, 55.6 percent of the gravity work and 31.4 percent of the ground magnetic work in the U.S.A. Corresponding figures for the previous year were 53.5 percent of the seismic work, 50.3 percent of the gravity work and 34.6 percent of the ground magnetic work. All airborne surveys in the United States were carried out by contracting companies.

## THE MINING INDUSTRY

Geophysical activity by the mining industry, as in the past, is presented in this report in manpower utilization expressed in professional man-months and in expenditures expressed in U. S. dollars. The manpower statistics include only professional employees who have college training or its equivalent in experience,

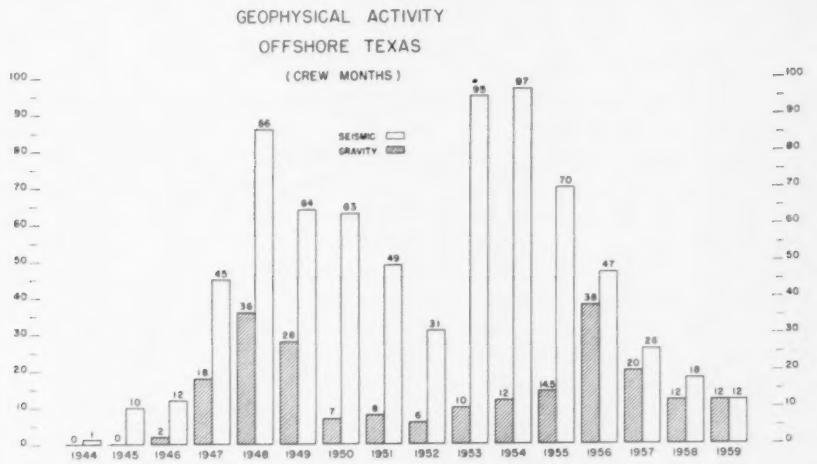


FIG. 8. Seismograph and gravimeter crew-months by years in the Texas portion of the Gulf of Mexico.

and who occupy professional or technical jobs. The utilization of professional manpower by the mining industry has increased and total expenditures have decreased in each of the past four years. The average number of professional people employed in mining geophysics increased from 796 in 1958 to 885 in 1959. Expenditures decreased from $9,901,000 in 1958 to $9,474,000 in 1959.

Figure 9 shows a breakdown of activity in mining geophysics according to the major areas of the world. In Figure 9 and Figure 10 to follow the bars at the left show the professional manpower utilized measured in man-months and the adjoining bars on the right show expenditures in U. S. dollars. The work carried out by governmental agencies is shown by slanted hachures. The portion of the work of private companies is subdivided according to that done by company-owned crews, shown in solid form and by contract crews, shown by vertical hachures. Geophysical exploration by the mining industry continued at a high level in the countries of Asia during 1959. The total effort in Asia, however, was below that of the previous year in both manpower utilization and expenditures. The average number of professional people engaged in mining geophysics in Asia declined from 319 in 1958 to 292 in 1959, while expenditures were reduced from $1,867,000 in 1958 to $1,657,000 in 1959. Government-sponsored surveys in Asia accounted for use of slightly more than half the professional personnel but accounted for less than half of the expenditures. Activity in mining geophysics was again high in Europe during the year. An increase in manpower utilization in Europe was reported as compared to the previous year but expenditures were reduced. The major portion of work reported in Europe was done by

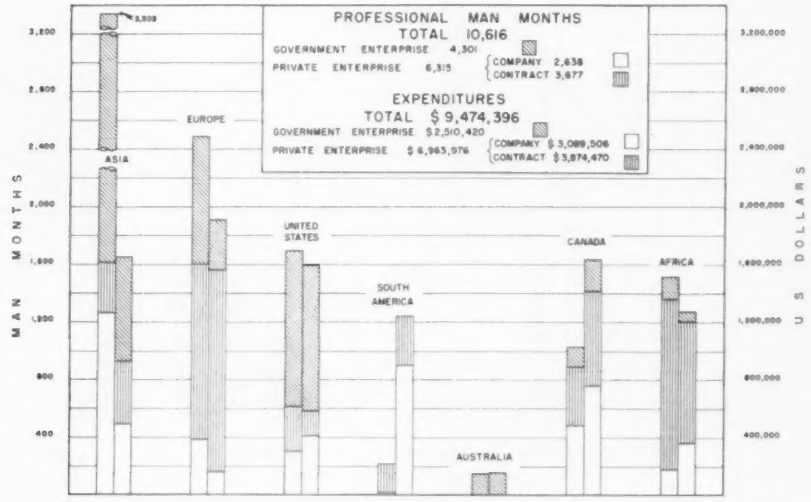


FIG. 9. Mining geophysics world-wide effort in 1959 by areas.

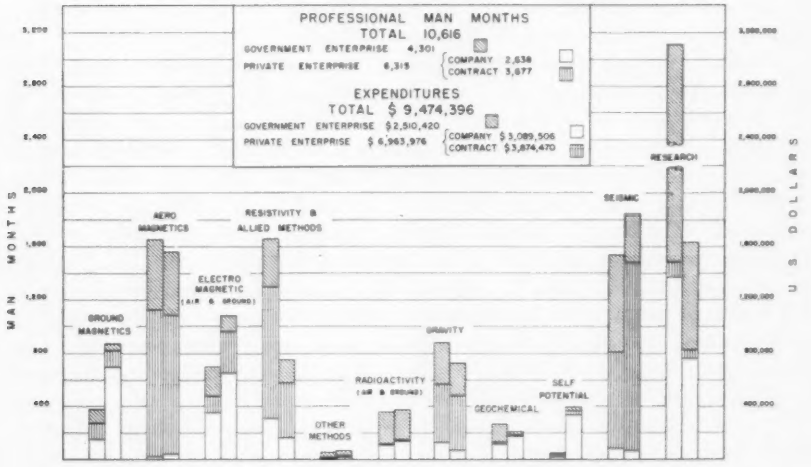


FIG. 10. Mining geophysics world-wide effort in 1959 by methods.

private companies using, for the most part, the services of contractors. Decreased activity was reported in the United States in 1959. In Canada activity was increased as compared to the previous year. The employment of professional personnel by the mining industry in Africa was substantially greater in 1959 than in 1958, but expenditures in Africa were less in comparison to the previous year. In professional manpower utilization the major areas of the world ranked in decreasing order as follows: (1) Asia, (2) Europe, (3) U.S.A., (4) Africa, (5) Canada, (6) South America, (7) Australia. Expenditures for mining geophysics in these areas ranked in decreasing order as follows: (1) Europe, (2) Asia, (3) Canada, (4) U.S.A., (5) Africa, (6) South America, (7) Australia.

Figure 10 shows the 1959 activity in mining geophysics according to methods. The seismic method, which has gained favor in mining exploration in recent years, was among the methods most widely used in 1959. Magnetic methods continued to be among those favored by the industry as did resistivity and allied electrical methods. The average number of professional geophysicists employed in seismic work for the mining industry in 1959 was 128 compared to 150 in 1958. Expenditures for seismic work, however, increased from $1,666,000 in 1958 to $1,833,000 in 1959. Expenditures for airborne magnetometer surveys during the year were only about half the 1958 expenditures, yet a larger number of professional people were employed in the work. Use of the electromagnetic method in 1959 was not up to the 1958 level in manpower utilized or expenditures. Fewer professional people were employed in ground magnetic surveys during 1959 than in the previous year but expenditures for the method were greatly increased. The use of professional people in carrying out resistivity and allied electrical methods increased from 845 man-months in 1958 to 1,645 man-months in 1959, while expenditures were up from $476,000 in 1958 to $751,000 in 1959. Increased use of the gravity, geochemical and self-potential methods was reported during the year. Decreased activity in exploration by radioactive methods as compared to the previous year was reported for 1959.

The use of geophysical exploration methods by the mining industry ranked in order of decreasing manpower utilization as follows: (1) Resistivity and allied electrical methods, (2) aeromagnetic, (3) seismic, (4) gravity, (5) electromagnetic, (6) ground magnetic, (7) radioactive, (8) geochemical, (9) other, (10) self-potential. The methods ranked in decreasing order of expenditures as follows: (1) seismic, (2) aeromagnetic, (3) electromagnetic, (4) ground magnetic, (5) resistivity and allied electrical methods, (6) gravity, (7) self-potential, (8) radioactive, (9) geochemical, (10) other.

Exploration and research work in mining geophysics carried out by governmental agencies during 1959 accounted for 40.5 percent of the professional manpower utilized and 26.5 percent of the total expenditures. In the previous year 65.5 percent of the professional geophysicists were employed in government-sponsored surveys, while expenditures for government-sponsored work in 1958 accounted for 36.1 percent of the total. During 1959 privately owned companies

utilized 59.5 percent of the total professional manpower in mining geophysics and accounted for 73.5 percent of the expenditures. Contract geophysical companies supplied 58.2 percent of the professional personnel employed by private enterprise and accounted for 55.6 percent of the expenditures by private industry during the year.

Geophysical research work was carried out by the mining industry during the year at about the 1958 level. The average number of research geophysicists employed in 1959 was 260 compared to 263 in 1958. Research expenditures amounted to $1,626,000 in 1959 compared to $1,612,000 the previous year. The research effort in mining exploration was about equally divided between governmental agencies and private enterprise.

# DEPARTMENTS

## DISCUSSION

### RECOMMENDED FORM FOR THE ACOUSTIC (CONTINUOUS-VELOCITY OR SONIC) LOG*

M. B. WIDESS†

At the annual meeting of the Southern Seismic Well Shooting Association held in Shreveport on April 4, a motion was passed recommending to SEG that the Society take steps toward formulation of a recommended standard form for the acoustic (continuous-velocity or sonic) log.

The motion, initiated before the Association by the writer, was prompted by the following two considerations:

1. API has set forth a recommended standard form for electrical and nuclear logs. Though these standards are also eminently suited to the acoustic log, the forms of acoustic logs in present use are frequently not compatible with the standards.

2. The so-called *corrected acoustic logs*, prepared particularly for geophysical application, are not compatible with field acoustic logs when the former utilize linear velocity instead of linear time scales. In general, acoustic logs utilizing linear time scale are better adapted to analysis, a circumstance that argues against standardizing on linear velocity scale for the corrected acoustic logs.

#### API STANDARDS

The American Petroleum Institute, Division of Production, has issued the following two reports, both dated September, 1959:

RP 31. Recommended Practice and Standard Form for Electrical Logs.
RP 33. Recommended Practice and Standard Calibration and Form for Nuclear Logs.

Both reports stipulate the following "standard log record":

1. All logs (electrical and nuclear) "should be printed on paper not over 9 inches or less than 8½ inches wide" (part of paragraphs 39 and 68 of RP 31 and RP 33 respectively).

2. "The horizontal grids used for many years of 50 ft of depth per inch of paper with five divisions per inch (2 inches = 100 ft) and 20 ft of depth per inch with ten divisions per inch (5 inches = 100 ft) are recommended as the standard practice" (part of paragraphs 40 and 69 of RP 31 and RP 33 respectively).

* Received by the Editor May 6, 1960.
† Pan American Petroleum Corporation, Fort Worth, Texas.

3. "The industry has also generally accepted a reproduction of the 2-inch log, reduced to $\frac{1}{2}$ size, for correlation purposes. Likewise, in some areas a 1-inch = 100 ft log is recorded directly" (paragraphs 53 and 73 of RP 31 and RP 33 respectively).

The standards set forth in the above reports are of course based on vast experience and take into account the fact that thousands of logs exist in company files. Needless to say, uniformity of depth scale between acoustic logs and those of electrical and nuclear logs is essential to effective absorption of acoustic log data in the exploration effort, essential to the geophysicist as well as the geologist and production engineer. A standard width of log is also necessary. For example, log cabinets that house the thousands of half-scale electrical and nuclear logs should also be able to contain the half-scale acoustic logs.

### LINEAR "TRANSIT TIME" SCALE ON CORRECTED ACOUSTIC LOGS

The acoustic log obtained in the *field* is linear in "transit time" rather than in velocity and is subject to certain inaccuracies. The *corrected acoustic log*, devised by the geophysicists to provide the finished product for routine geophysical operations, accounts for check shot data obtained from the conventional well shooting survey and may also adjust for wash-out spikes. In addition, the present tendency is to express the corrected acoustic log in terms of linear velocity, the unit that is most familiar to the geophysicist. This inclination toward preparing corrected acoustic logs in terms of linear velocity while the field logs are in terms of linear "transit time" is unfortunate. The corrected acoustic log, no longer the original data alone, involves interpretation by the individual preparing that log, an interpretation that may depart significantly from the opinion of interpreters in other companies who receive the log in trade or sale. Since few geophysical departments are willing to accept without examination the interpretational opinion of other companies, there is considerable merit in having a corrected acoustic log in a form such that it can be easily compared with the field log to perceive and evaluate the nature of the corrections that were applied. The comparison can be accomplished without great labor only if the corrected acoustic log has the same scales as the field log. It is therefore highly desirable to have a corrected acoustic log in linear "transit time" rather than in linear velocity.

There is much more that may be said for linear "transit time" scale. Like reflection data in reflection surveys, acoustic log data consist of time measurements. Accordingly, again as in reflection surveying, maximum flexibility of handling the data and maximum capacity for evaluating the data as such are provided if time is retained as the working medium. This is indicated for example by the fact that when two receivers are used, the integral of the acoustic log cancels the effect of a wash-out much more effectively if the acoustic log is expressed in linear "transit time" than if it is expressed in linear velocity. And of course an error in instrumental calibration produces a fixed error in "transit

time" but not a fixed error in velocity. Furthermore, correction for check shot data is applied in terms of "transit time" not in terms of velocity.

Advantages of linear time scale accumulate also for the corrected acoustic log. But first it would be well to dispel the misconception that reflection coefficients are more coherent on linear velocity scale. The equation for the reflection coefficient $R_c$ from an interface is

$$R_c = (V_2 - V_1)/(V_2 + V_1), \tag{1}$$

for vertical incidence and neglecting density change. Since $V = k/t$ (where $t$ is the "transit time" over distance $k$), the equation becomes

$$R_c = (t_1 - t_2)/(t_1 + t_2). \tag{2}$$

The symmetry between equations 1 and 2 shows that interfaces giving the same magnitude of reflection coefficients along the log are just as easily identified on a linear "transit time" scale as on a linear velocity scale[1] (a logarithmic scale, either in "transit time" or velocity, would of course be better in this regard than either a linear "transit time" or linear velocity scale).

An important advantage of using a linear "transit time" scale on the corrected acoustic log stems from the adaptation of the log to computing synthetic reflections. In digitizing the acoustic log, it is of course essential that the reflection time be conserved. Since the length of the acoustic log utilizes a depth ($D$) scale, one-way reflection time $T$ is simply

$$T = \int (1/V)dD, \tag{3}$$

which is

$$T = (1/k)\int t\,dD, \tag{4}$$

so that an increment $\Delta T$ of reflection time is

$$\Delta T \cong (1/k)t\Delta D. \tag{5}$$

Thus, to retain correct reflection time, the digitized value of the "transit time" $t$ is simply the *mean* "transit time" over the depth interval $\Delta D$. The relation is of course the basis for the integrated time that is recorded on acoustic logs in general.

[1] Though equations 1 and 2 are symmetric, the high velocity range of the acoustic log covers a greater proportion of a linear velocity scale than of a linear "transit time" scale, assuming that overall ranges for both scales are comparable. In some cases this may be an advantage for the linear velocity scale, but not enough to offset its disadvantages. An alternative is to include a second curve utilizing a larger scale of linear "transit time" for the high velocity range. Incidentally, an advantage from linear velocity scale has also sometimes been suggested on the basis that porosity may be linearly related to velocity. However present data indicates that porosity is no more, and possibly less, linear with velocity than with "transit time."

Linear "transit time" scale is also better suited for handling reflection coefficients. For example, for a thin layer of velocity $V_2$ imbedded in a medium of velocity $V_1$, the reflection coefficient $R_c'$ is[2]

$$R_c' \cong \frac{4\pi}{\tau} \frac{V_2 - V_1}{V_2 + V_1} \left(\frac{b}{V_2}\right), \tag{6}$$

where $b$ is the thickness of the bed in ft and $\tau$ is the predominant period of the recorded wavelet. The equation can then be expressed in the form

$$R_c' \cong \frac{4\pi}{\tau} \left\{ \frac{1}{V_2(V_2 + V_1)} \right\} [(V_2 - V_1)b]. \tag{7}$$

Now compare this equation with its equivalent expressed in terms of "transit time" $t$ (where $V = k/t$), namely

$$R_c' \cong \frac{4\pi}{k\tau} \left\{ \frac{t_2}{t_1 + t_2} \right\} [(t_1 - t_2)b]. \tag{8}$$

The terms enclosed by the brackets constitute the area on the acoustic log associated with the thin bed for a linear velocity scale (equation 7) and a linear "transit time" scale (equation 8). In digitizing, the interfaces are often moved to accommodate the minimum increment of reflection time that is used. The terms enclosed by the braces indicate the degree of error that would result if the area on the acoustic log were to be used solely as the basis for the digitizing. Since, in the braced terms, velocity appears only in the denominator, while "transit time" appears both in the numerator *and* the denominator, the error introduced when linear velocity scale is used is considerably greater than when linear "transit time" scale is used.[3] Digitizing an acoustic log of course constitutes a smoothening of the original data. A linear "transit time" scale facilitates higher accuracy in the smoothening process.

## THE NEED FOR A BETTER LABEL FOR RECIPROCAL VELOCITY

It is not surprising, albeit unfortunate, that the geophysicist has a tendency at present to favor linear velocity rather than reciprocal velocity on (corrected)

[2] Widess, M. B., 1957–1958, How thin is a thin bed: The Proceedings of the Geophysical Society of Tulsa, v. 5, p. 20, equation 4. A thin bed is defined here as one whose thickness is less than about one eighth of the wave length computed using the velocity of the bed.

[3] For example, let $V_2'$ be the velocity used instead of $V_2$ to preserve the area while changing the position of the interfaces. If $V_2'/V_2 = 0.9$ and $V_2/V_1 = 1.5$, $R_c'$ as given by equation 7 is an error by 18 percent. If linear "transit time" is used instead, the corresponding conditions are $t_2'/t_2 = 1/0.9$ and $t_1/t_2 = 1.5$, and $R_c'$ as given by equation 8 becomes in error by only 6 percent.

These relations apply to the conventional acoustic logs utilizing linear depth scale. If a linear reflection-time scale is used instead, both a linear velocity scale and a linear "transit time" scale lead to the smaller magnitude of error in the above example. The acoustic log that is in many ways best for geophysical application is of course one that uses a linear reflection-time scale. But this is another topic, and in the same vein one may add that at present the best medium for the log is magnetic tape.

acoustic logs. "Velocity" is an integral part of his everyday language, while there is no suitable single word in the English language, nor any other language to the writer's knowledge, that means reciprocal velocity. The history of science amply demonstrates that man cannot think comprehensively in terms of a particular concept until a label is applied to that concept. Should a succinct and catchy label for reciprocal velocity have already been in existence, it is likely that the term would have been in common usage among geophysicists even before the advent of acoustic logging. An analogy occurs for example in "frequency" (cycles per second) and its reciprocal, "period." Science could hardly get along without both these terms.

The writer does not believe that "transit time" is an adequate label for reciprocal velocity (and it probably was not intended to be that by its present users) because it implies time through a specific zone rather than an intrinsic property of the material within the zone. Perhaps "time-modulus" (or its abbreviation "timemod") would be more appropriate, even though the unit is not time alone. The terms "time constant" and "time decrement" occur in the technical vocabulary, but not "time modulus."

The basic unit of reciprocal velocity in the English system is of course "seconds per foot." The fact that this leads to magnitudes of microsec/ft for seismic velocities does not need to pose a problem since the same numerical value also applies to millisec/thousand ft, a unit that is well suited to geophysical applications.

# PATENTS

O. F. RITZMANN†

## ELECTRICAL PROSPECTING

*U. S. No. 2,929,984.* M. Puranen, A. A. Kahma, and V. Ronka. Iss. 3/22/60. Appl. 1/12/56. Assign. Canadian Airborne Geophysics Ltd.

*Method and Apparatus for Qualitative Electromagnetic Surveying.* An airborne electromagnetic prospecting system having on the airplane a primary coil excited at two frequencies and two tuned coils to pick up the respective frequencies, the quadrature component of the picked-up signal from each coil being recorded.

*U. S. No. 2,931,972.* A. E. Tilley. Iss. 4/5/60. App. 7/24/56. Assign. California Research Corp.

*Apparatus for Resistivity Surveying of the Earth.* A four-electrode resistivity prospecting system in which the potential electrodes are alternately connected to the measuring circuit and to an earth-current compensating circuit, each circuit being automatically adjusted by a servo-system that synchronously balances the measuring potentiometer and the compensating potentiomter.

*U. S. No. 2,931,973.* M. Puranen. Iss. 4/5/60. Appl. 10/24/57. Assign. Canadian Airborne Geophysics Ltd.

*Electromagnetic Exploration Method.* A method of airborne electromagnetic prospecting using horizontal and vertical exciting coils that are alternately energized for short intervals with a-c, and having two receiving coils at right angles in a towed bird, the difference in the picked-up signals being recorded.

## GRAVIMETRIC PROSPECTING

*U. S. No. 2,926,842.* H. A. Ackerman. Iss. 3/1/60. App. 3/27/57. Assign. Socony Mobil Oil Co., Inc.

*Apparatus for Determining Horizontal and Vertical Gradients of Gravity.* A geometrical device for the mechanical determination of the vertical and horizontal gradients of gravity from gravity meter readings taken at three stations from 50 to 100 ft apart and at least one of which is at a different elevation from the others.

*U. S. No. 2,928,667.* R. H. Peterson. Iss. 3/15/60. App. 8/24/53. Assign. Radio Corporation of America.

*Gravitational or Accelerational Responsive Device.* A device for stabilizing a gimbal-mounted platform and having two revolving masses connected to an axially movable diaphragm that controls a shaft by means of levers, so that asymmetry of forces on the masses moves the shaft and the shaft motion is detected, analyzed as to phase, and delivered to orienting servo motors acting on the gimbal support.

*U. S. No. 2,930,138.* L. J. B. LaCoste. Iss. 3/29/60. App. 6/16/55. Assign. LaCoste & Romberg.

*Leveling Device for Indicating Units.* A self-leveling gimbal-suspended instrument having a mechanical damping brake that is periodically actuated and released by a motor and is connected in an indicating circuit so that the motor can be stopped with the brake on for transporting the instrument or off when reading the instrument.

See also Patent 2,934,652 listed under WELL LOGGING.

† Gulf Oil Corporation, Patent Department.

MAGNETIC PROSPECTING

*U. S. No. 2,928,044.* R. Schulze. Iss. 3/8/60. App. 12/9/56 and 12/9/57. Assign. Askania-Werke A. G.

*Recording Magnetometer.* A suspended-magnet optically recording type of magnetometer having an auxiliary compensating magnet that is suspended so as to turn about an axis parallel to that of the recording magnet, the auxiliary magnet having a high moment of inertia so that it can adjust itself for recording slow magnetic changes but rapid magnetic pulsations are recorded without change in compensation.

*U. S. No. 2,929,018.* R. H. Varian. Iss. 3/15/60. App. 5/11/54. Assign. Varian Associates.

*Gradiometer.* A magnetic gradiometer having two magnetometers each of which has a magnetic core with two air gaps containing a gyromagnetic substance in the side arm of a magic T that determines the frequency of a microwave oscillator so that the difference of the two oscillator frequencies is a measure of the field strength, and the difference between the magnetometer indications is a measure of the gradient.

*U. S. No. 2,929,019.* J. F. Bryan and J. R. Patmore. Iss. 3/15/60. Appl. 12/14/55. Assign. Electronic Associates, Inc.

*Magnetic Field Detection.* A magnetic curve follower having a magnetic core with a bifilar center-tapped winding whose ends are connected to silicon junction diodes and to a circuit for developing a d-c output indicative of the lateral displacement of the core from the curve.

*U. S. No. 2,930,974.* O. C. From. Iss. 3/29/60. App. 8/1/57. Assign. International Telephone and Telegraph Corp.

*Magnetic Field Detecting Device.* A mechanically indicating magnetic field detector for indicating operation of a totally enclosed electrical relay.

*U. S. No. 2,931,974.* G. H. McLaughlin, H. A. Harvey, W. O. Cartier, and W. A. Robinson. Iss. 4/5/60. App. 6/30/54. Assign. Crossland Licensing Corp. Ltd.

*Method of Geophysical Prospecting.* A magnetic prospecting system in which time transients of the earth's field are observed at different points throughout an area and compared to locate anomalies that are independent of time and caused by subterranean bodies.

*U. S. No. 2,933,059.* S. B. Cohen, R. Scheib, Jr. and V. Vacquier. Iss. 4/19/60. App. 10/28/53. Assign. Sperry Rand Corp.

*Shipboard Degaussing System.* A degaussing system in which the relationship of the ship and the earth's magnetic field is reproduced by means of a-c excited coils producing fields representing the components of the earth's field, the sysem being stabilized with respect to magnetic orientation, with pick-up detectors corresponding to the ship's degaussing coils to detect variations in the a-c field as the ship's attitude changes, and the detected signals used to control d-c generators connected to the degaussing coils.

RADIOACTIVITY PROSPECTING

*U. S. No. 2,938,965.* R. T. Bayard and T. J. Walker. Iss. 3/15/60. Appl. 10/27/54. Assign. Westinghouse Electric Corp.

*Neutron Detector.* A fast neutron detector having a number of elongated thermal neutron counters connected in parallel and inserted in holes in blocks of neutron moderating material.

*U. S. No. 2,929,932.* G. M. B. Bouricius and G. K. Rusch. Iss. 3/22/60. App. 4/23/57. Assign. U.S.A.

*Radiation Measuring Devices.* A neutron detector having an emitter from which neutrons emit

charged particles that are accelerated and alternately deflected to two collector plates by deflecting electrodes connected to a source of a-c, the resulting a-c between the collector plates being filtered and indicated.

*U. S. No. 2,932,741.* A. S. McKay. Iss. 4/12/60. App. 2/28/57. Assign. Texaco Inc.

*Method of Tracing Fluid Streams.* A tracing technique in which the tracer is introduced into one stream with a time pattern and into another stream with a different time pattern, and the tracer detected downstream and the streams identified by the observed time patterns.

*U. S. No. 2,933,923.* S. W. Milochik. Iss. 4/26/60. App. 8/20/56.

*Method for Detecting Underground Radioactive Deposits.* A thermal prospecting system in which holes are drilled about six ft deep in a specified pattern and the earth temeprature measured at the bottom of the holes.

SEISMIC PROSPECTING

*U. S. No. 2,926,739.* W. E. Shoemaker. Iss. 3/1/60. App. 1/20/55. Assign. California Research Corp.

*Apparatus for Controling Initiation of Seismic Disturbances.* A remotely controlled shot firing system in which power is supplied to the detonator through an electronically controlled flash tube that is triggered by the recorder.

*U. S. No. 2,927,300.* N. J. Smith. Iss. 3/1/60. Appl. 6/20/55. Assign. California Research Corp.

*Cancellation of Seismic Surface Noise.* A system for cancelling the effect of transverse waves by combining with signals from a longitudinally polarized geophone, signals from one or more geophones sensitive to the rotational component of the transverse wave with appropriate phase shift.

*U. S. No. 2,928,070.* E. M. Palmer, W. E. Wickerham, and R. D. Wyckoff. Iss. 3/8/60. App. 4/28/58. Assign. Gulf Research & Development Co.

*Amplitude Record Conversion Apparatus.* An automatic device for making a multi-trace variable density record from a succession of variable-area recordings and in which a galvanometer light beam is controlled by a servocircuit to follow the contour of the v-a record and the galvanometer signal is amplified and used to operate a v-d lamp that records on a record rotating with the v-a record.

*U. S. No. 2,928,179.* T. A. Garrity, Jr. Iss. 3/15/60. App. 9/24/57. Assign. The Pure Oil Co.

*Problem Solving Device.* A mechanical computing device for determining the magnitude and direction of dip of a reflecting horizon from the observed seismic move-out times along two orthogonal lines.

*U. S. No. 2,928,489.* E. G. Perry. Iss. 3/15/60. App. 4/13/55. Assign. Texas Instruments Inc.

*Seismic Record Viewer.* A device for temporarily recording a filtered seismogram on a phosphorescent drum by means of an optical oscillograph so that the record can be optically viewed for determining optimum filter adjustments.

*U. S. No. 2,928,668.* B. P. Blasingame. Iss. 3/15/60. App. 6/5/59.

*Accelerometer.* An accelerometer having two reeds back to back and maintained in continuous vibration, acceleration along the axis of the reeds being determined by observing the change in the difference between the frequencies of the reeds.

*U. S. No. 2,929,020.* F. M. Mayes. Iss. 3/15/60. App. 4/19/55. Assign. Sun Oil Co.

*Apparatus for Impedance Measurements.* An impedance measuring circuit for use with a capacitance transducer having two shunted condensers and two diodes in a balanced bridge circuit excited at two frequencies, and the difference frequency arising from unbalance of the condensers is fed by a

cable to a cathode follower whose signal is filtered and indicated by means of a synchronous rectifier, the output of the cathode follower also being used to control the potential on the cable sheath.

*U. S. No. 2,929,669.* P. E. Madeley and F. W. Hefer. Iss. 3/22/60. App. 7/9/56. Assign. Dresser Industries, Inc.

*Timing Line Numbering Apparatus.* A system for counting magnetic timing impulses and photographically putting on an oscillographic record the timing line count during the process of transcribing a magnetic seismogram into visual form.

*U. S. No. 2,929,986.* F. M. Mayes. Iss. 3/22/60. App. 4/19/55. Assign. Sun Oil Co.

*Apparatus for Impedance Measurements.* An impedance measuring circuit for use with a capacitance transducer in which two shunted condensers and two diodes in a bridge circuit are excited by a-c so that harmonics are generated which are detected by a cathode follower connected to a filter and synchronous rectifier whose output is indicated.

*U. S. No. 2,930,276.* G. H. Smith and W. J. Mitchell. Iss. 3/29/60. App. 7/25/55. Assign. Union Carbide Corp.

*Charging Blast Holes with Explosive.* A method of loading a liquid oxygen type explosive into a shot hole by inserting a collapsed inflatable bag around a pipe into the hole, filling the annular space between the pipe and the bag with carbonaceous combustible material, and injecting liquid oxygen to the bottom of the hole through the pipe.

*U. S. No. 2,930,669.* J. C. R. Kicklider. Iss. 3/29/60. App. 10/25/56. Assign. California Research Corp.

*Seismic Data Display.* An oscillographic recording system using a reflecting galvanometer and multiple light sources arranged so that as the light beam from one source is deflected off the channelized track, the next light beam enters the track, and all parts of a large galvanometer deflections are successively recorded on a relatively narrow track.

*U. S. No. 2,932,001.* V. T. Reynolds. Iss. 4/5/60. App. 2/14/57.

*Seismic Record Plotter.* An apparatus for transcribing magnetically recorded seismograms into a visual record by simultaneously scanning the record tracks and rerecording by means of galvanometers, the scanning heads being displaced with respect to each other during the transcription to effect time-varying corrections.

*U. S. No. 2,932,002.* M. Keiser. Iss. 4/5/60. App. 4/23/53 and 7/22/57. Assign. U.S.A.

*Acoustic Position Finder.* A sound ranging system whose microphones are connected to magnetic recording heads recording on disks on a common shaft with the head circuits and circuits to separate erasing heads controlled by a common switch, and with the position of the magnetic reproducing head on each disk being adjustable so as to permit introduction of time delays for analysis purposes.

*U. S. No. 2,932,357.* G. White. Iss. 4/12/60. App. 2/8/55. Assign. Texas Instruments Inc.

*Method and Apparatus for Recording Seismic Signals.* A seismic prospecting system in which the seismometer signals are recorded through filter amplifiers with avc and the signal from at least one seismometer is recorded without filtering through a logarithmic compressor amplifier and also with filtering through a logarithmic compressor amplifier.

*U. S. No. 2,932,547.* M. L. Swan. Iss. 4/12/60. App. 6/28/55. Assign. United Geophysical Corp.

*Seismic Wave Recording System.* A system for producing coded timing lines on a magnetic or photographic seismogram having an oscillator feeding a pulse generator that produces short-interval pulses of one polarity and larger pulses of opposite polarity at ten times longer interval, the two sets of

pulses being separately recorded on a magnetic record and recorded on a single track on a photographic record by means of a glow tube.

*U. S. No. 2,933,653.* E. P. Carter. Iss. 4/19/60. App. 2/4/55. Assign. E. I. du Pont de Nemours and Co.

*Blasting Machine.* A shot firing circuit having a transformer whose core has a rectangular hysteresis loop and has three windings, application of d-c to the primary coil producing firing current in the secondary coil and a shot-moment signal in the tertiary coil.

*U. S. No. 2,933,715.* W. Beuermann. Iss. 4/19/60. App. 4/21/56 and 4/19/57. Assign. Firma Seismos, G.m.b.H.

*Seismic Device.* A seismometer having a hinged arm carrying a mass and connected to a cantilever spring and having at the end of the arm a coil moving in a pot magnet.

*U. S. No. 2,934,741.* N. E. Gray and A. E. Tilley. Iss. 4/26/60. App. 1/16/56. Assign. California Research Corp.

*Calibrated Automatic Gain Control for Seismic Amplifiers.* A seismograph avc system having a reference signal with which the seismic signal is compared and the error signal used to control a servomotor that adjusts a continually variable attenuator in the seismograph channel.

See also Patents 2,927,656, 2,928,071 and 2,933,144 listed under WELL LOGGING; and Patents 2,928,367, 2,931,566, 2,931,567 and 2,931,690 listed under MISCELLANEOUS.

### WELL LOGGING

*U. S. No. 2,927,301.* S. E. Booth and E. H. Ward. Iss. 3/1/60. App. 7/2/53 and 6/8/54. Assign. The British Petroleum Co. Ltd.

*Measurement of Liquid Levels in Wells.* A sonic fluid level measuring apparatus using a mechanically actuated rubber diaphragm as a low frequency source and a hot wire microphone as detector.

*U. S. No. 2,927,377.* D. B. McMahan. Iss. 3/8/60. App. 6/6/57. Assign. Welex, Inc.

*Opening and Closing Device for Well Bore Caliper.* A motor-driven hydromechanical device for retracting or releasing the arms of a caliper logging apparatus.

*U. S. No. 2,927,459.* W. B. Farrington. Iss. 3/8/60. App. 7/18/57. Assign. Jersey Production Research Co.

*Measurement of Subsurface Stress.* An apparatus for accurately measuring deformation of the borehole wall by having opposed plungers that are mechanically forced against the wall with a known stress and the extension of the plungers measured with the same stress when the hydrostatic pressure on the hole is changed.

*U. S. No. 2,927,656.* F. J. Feagin, M. R. MacPhail, and W. M. Rust, Jr. Iss. 3/8/60. App. 8/28/53. Assign. Jersey Production Research Co.

*Method and Apparatus for Interpreting Geophysical Data.* A system for correlating two well logs or seismograms in which the signals are recorded on a magnetic drum and reproduced with relative displacement by movable magnetic heads whose signals are electronically operated on to determine the value of a desired correlation criterion.

*U. S. No. 2,927,954.* F. H. Ellsworth. Iss. 3/8/60. App. 9/27/56. Assign. United States Steel Corp.

*Shielded Oil Well Cable.* A multi-conductor well-logging cable having a plastic shielding material around the conductors, the shielding material containing carbon particles to impart conductivity.

*U. S. No. 2,928,038.* R. H. Huddleston, Jr. Iss. 3/8/60. App. 10/5/56. Assign. Welex, Inc.

*Electromagnetic Well Logging System.* An electromagnetic logging system having a primary coil excited at constant current and a secondary coil connected to a phase-sensitive synchronous detector whose d-c output is used to modulate a low frequency signal which is transmitted to the surface by an f-m transmission system.

*U. S. No. 2,928,039.* R. H. Huddleston, Jr. Iss. 3/8/60. App. 10/5/56. Assign. Welex, Inc.

*Constant Electromagnetic Field Well Logging System.* An electromagnetic logging system in which the exciting coil current also passes through a temperature-sensitive resistor in a bridge circuit and the bridge unbalance is used to control the a-c supply so as to keep the exciting current constant.

*U. S. No. 2,928,071.* F. J. Feagin. M. R. MacPhail, and W. M. Rust, Jr. Iss. 3/8/60. App. 1/15/59. Assign. Jersey Production Research Co.

*Interpretation of Geophysical Data.* An apparatus for correlating well logs in which the logs are recorded on a magnetic drum, reproduced with relative displacement by movable magnetic heads whose signals are subtracted, squared, and integrated to determine the value of a correlation function for the displacement used.

*U. S. No. 2,929,244.* G. J. Butterworth and S. W. Gurasich. Iss. 3/22/60. App. 10/2/51, 5/17/55, and 7/19/55. Assign. Sperry-Sun Well Surveying Co.

*Self-Contained Flowmeter.* A self-contained well flowmeter having an impeller whose rotations are counted and recorded as dots on an electrochemical recording medium driven by a clock.

*U. S. No. 2,929,863.* R. H. Carlson. Iss. 3/22/60. App. 10/17/56. Assign. United States Steel Corp.

*Insulated Oil Well Cable.* A well-logging cable whose conductors are insulated with a butadiene-styrene polymer.

*U. S. No. 2,930,137.* J. J. Arps. Iss. 3/29/60. App. 8/4/54.

*Earth Borehole Crookedness Detection and Indication.* A system for determining eccentricity of the drill collars in a borehole while drilling by having electrodes on the outside of the drill collar connected to an electric circuit that includes a solenoid valve for setting up pressure surges in the column of drilling fluid, the pressure surges being detected and recorded at the surface.

*U. S. No. 2,930,967.* W. M. Laird and M. R. J. Wyllie. Iss. 3/29/60. App. 12/29/53. Assign. Gulf Research & Development Co.

*Method and Apparatus for Logging Drilling Fluid.* A drilling fluid logging system in which an electrochemical ion-concentration emf is obtained for the circulating fluid entering the well and for fluid leaving the well, and the emf's compared and recorded.

*U. S. No. 2,930,968.* M. C. Ferre. Iss. 3/29/60. App. 5/31/56. Assign. Schlumberger Well Surveying Corp.

*Apparatus for Electrical Well Logging.* An a-c electric logging system using auxiliary focusing electrodes whose current is controlled by a self-oscillating network of variable gain that also controls the gain of a feedback loop including the measuring electrodes.

*U. S. No. 2,930,969.* J. S. Baker. Iss. 3/29/60. App. 5/16/56. Assign. Dresser Industries, Inc.

*Electrical Earth Borehole Logging Apparatus.* An electric logging sonde having a central body portion surrounded by an inflatable sleeve of insulating material that carries electrodes on its outer surface, the lower end of the sleeve having a smaller opening than the upper end so that the sleeve expands into contact with the borehole wall when it is pulled up the hole.

*U. S. No. 2,931,225.* F. W. Pleuger. Iss. 4/5/60. App. 8/24/54 and 8/23/55.

*Instrument for Indicating Oil Level, Ground Pressure and Temperature in an Oil Well.* An electric pressure gauge having a tube with an axial resistance wire that is short circuited by mercury connected to a pressure bulb with the wire connected in a bridge circuit with a crossed-coil indicator.

*U. S. No. 2,931,440.* M. P. Lebourg. Iss. 4/5/60. App. 3/15/56. Assign. Schlumberger Well Surveying Corp.

*Centralizing Means for Borehole Apparatus.* A centalizer for a logging apparatus having three substantially rigid arms one end of which is held by a screw that shears off if a tight spot is encountered.

*U. S. No. 2,931,455.* R. J. Loofbourrow. Iss. 4/5/60. App. 4/22/50 and 3/29/56. Assign. Texaco Inc.

*Acoustic Logging of Wells.* An acoustic logging system using recurring supersonic wave trains and two spaced receivers on the same side of the source, the received signals being amplified and a signal proportional to their time difference generated in the sonde and transmitted up the cable.

*U. S. No. 2,931,565.* H. S. Flick. Iss. 4/5/60. App. 9/19/55. Assign. BJ Service, Inc.

*Differential Volume Computer.* A computer for determining the volume of cement required for a casing cementing operation in which a caliper controls two ball and disk integrators that are initially set to the casing diameter and whose outputs are combined and actuate a counter that indicates the annular volume.

*U. S. No. 2,932,190.* O. V. Phillips. Iss. 4/12/60. App. 10/18/54. Assign. The Star Recorder Corp. of Denver.

*Tension Apparatus for a Cable Used with Recording Apparatus for Earth Bore Drilling.* A drilling-rate recorder having a cable to the traveling block of the drilling ring wound on an axially shiftable reel for selecting recording or free running, and having a clamp for locking the cable when the reel is shifted.

*U. S. No. 2,932,740.* R. H. Widmyer. Iss. 4/12/60. App. 4/18/56. Assign. Texaco Inc.

*Borehole Fluid Mixing Apparatus.* An apparatus for measuring a characteristic of well fluid having a series of baffle plates below the detecting instrument so as to agitate and mix the well fluid as it flows past the detector.

*U. S. No. 2,933,144.* J. G. Scott, R. A. Freeman, and R. T. Houston. Iss. 4/19/60. App. 8/12/54. Assign. American Percussion Tool Co.

*Well Logging Method and Apparatus.* A system of logging while drilling in which the drill is impacted at a constant frequency and signals from seismometers at different azimuths around the well are compared in phase with the source signal.

*U. S. No. 2,933,609.* R. G. Norelius. Iss. 4/19/60. App. 5/11/54. Assign. Dresser Industries, Inc.

*Radioactivity Well Surveying.* A logging system using a neutron source and two radiation detectors spaced different axial distances from the source and comparing the indications to distinguish formation effects from those due to the invasion of borehole fluid into the formation.

*U. S. No. 2,933,674.* N. A. Schuster. Iss. 4/19/60. App. 8/6/56. Assign. Schlumberger Well Surveying Corp.

*Well Logging Systems.* An a-c electrical resistivity logging system using auxiliary focusing electrodes whose current is supplied by a variable-gain amplifier and measuring the phase angle between potential picked up at the potential electrodes and the energizing current.

*U. S. No. 2,933,819.* J. C. Kinley. Iss. 4/26/60. App. 6/12/52, 10/1/56, and 11/27/56. Assign. One-half to Myron M. Kinley.

*Internal Pipe Calipering Tools.* A device for recording the minimum and the maximum radius inside a pipe by means of feelers in the form of levers hinged on the instrument and having two actuating surfaces that respectively contact a convex and a concave follower whose motion is mechanically recorded on a chart.

*U. S. No. 2,933,820.* R. A. Bobo and S. Hoch. Iss. 4/26/60. App. 11/23/56. Assign. Phillips Petroleum Co.

*Borehole Inclinometer.* An inclinometer having a pendulum that contacts an appropriate contact to complete a circuit to one of a number of ball-ejection devices, the balls being caught on the shale shaker and being of distinctive color to indicate the degree of inclination.

*U. S. No. 2,934,652.* R. L. Caldwell, G. L. Hoehn, Jr., and T. W. Bonner. Iss. 4/26/60. App. 8/13/56. Assign. Socony Mobil Oil Co., Inc.

*Selected Scattered Gamma-Ray Density Logging.* A gamma-gamma density logging system using a collimated beam of incident gamma rays and a collimated beam of detected gamma rays, the intersection of the collimation directions occurring in the formation and the angle between them being the angle of Compton scattering for the energy band employed.

*U. S. No. 2,934,695.* R. M. Maulsby. Iss. 4/26/60. App. 4/26/55. Assign. Dresser Industries, Inc.

*Means for Indicating Length of Apparatus-Suspending Element in Earth Borehole.* A cable length marker made by including an annular short-circuited conductor at predetermined points in the cable, the marker being detected by running the cable through a pair of coils whose impedance unbalance is indicated.

*U. S. No. 2,934,697.* M. M. Hawthorne. Iss. 4/26/60. App. 4/12/55. Assign. Dresser Industries, Inc.

*Earth Well Tubing Anomaly Detector.* A magnetic pipe-joint detector having an axial bar magnet with disk-shaped pole pieces at each end and an intermediate annular pole piece radially spaced from the magnet and with an electron-beam type magnetic pick-up tube between the magnet and the intermediate pole piece to detect distortion of the flux pattern.

See also Patent 2,932,741 listed under RADIOACTIVITY PROSPECTING, and Patent 2,931,963 listed under MISCELLANEOUS.

### MISCELLANEOUS

*U. S. No. 2,928,177.* S. W. Wilcox. Iss. 3/15/60. App. 5/29/53. Assign. Seismograph Service Corp.

*Mechanical Indicating and Plotting Device.* A curve plotting device having a pair of rotatable arms connected by an endless tape on a frame with an adjustable slide that may be clamped to the tape.

*U. S. No. 2,928,178.* S. W. Wilcox. Iss. 3/15/60. App. 5/29/53. Assign. Seismograph Service Corp.

*Mechanical Plotting and Measuring Apparatus.* A device for drawing geometric curves and which can be used as a plotting unit for use with radio position determining apparatus of the hyperbolic phase type.

*U. S. No. 2,928,367.* J. C. McCormick. Iss. 3/15/60. App. 8/31/53.

*Means for Regulating the Depth a Submarine Device Tows Through Water.* A submarine tow having elevator fins that are mechanically controlled by bellows under air pressure from a pressure bellows mounted on a sled that rides on the floor of the body of water.

*U. S. No. 2,929,060.* B. W. Koeppel. Iss. 3/15/60. App. 3/20/57. Assign. Seismograph Service Corp.

*Radio Location System.* A phase-comparison type of radio position-finding system in which the link station and the receiver have filtered avc circuits that prevent a strong signal from overriding a weak signal and producing erroneous phase meter indications.

*U. S. No. 2,930,037.* D. G. Jones. Iss. 3/22/60. App. 3/20/57. Assign. Seismograph Service Corp.

*Ambiguity Resolution in Radio Location Systems.* A phase-comparison type of radio position-finding system in which the outputs from the phase-comparison units operate a pointer on a lane-counting instrument, one such instrument providing a coarse count of the hyperbolic lanes and the other a fine count.

*U. S. No. 2,931,566.* R. M. Strassner. Iss. 4/5/60. App. 12/20/54. Assign. Consolidated Electrodynamics Corp.

*Apparatus for Reading the Amplitude of Visibly Recorded Curves.* An oscillograph trace-reading system in which a galvanometer light beam transversely scans the record when triggered by a timing line, the transverse position of the trace being photoelectrically detected and the equivalent galvanometer voltage digitalized and indicated.

*U. S. No. 2,931,567.* E. M. Palmer. Iss. 4/5/60. App. 1/24/56. Assign. Gulf Research & Development Co.

*Apparatus for Controlling an Analog Computer.* A system for adjusting an element of an analog computer by punching an analog of the required adjustment in an electrically non-conducting card, scanning the card and synchronously varying the adjustment of the computer element, both the scanning and the adjustment being stopped by a signal when the card-scanning device senses a perforation.

*U. S. No. 2,931,690.* H. I. Chambers, A. W. Fischer, K. E. Sihvonen, and G. P. Wilson. Iss. 4/5/60. App. 6/21/56. Assign. Consolidated Electrodynamics Corp.

*Oscillograph Apparatus.* A direct recording string galvanometer having a signal-carrying conductor in a magnetic field so that the conductor moves transversely to motion of the recording medium and marks the medium by a potential applied between the conductor and a support for the medium, and with the conductor continuously vibrated longitudinally to keep it from sticking.

*U. S. No. 2,931,857.* J. H. Hammond, Jr. and E. L. Chaffee. Iss. 4/5/60. App. 9/23/55. Assign. J. H. Hammond, Jr.

*Television Reconnaissance System.* A system for transmitting ground observations from an airplane in which a moving mirror immobilizes the image of the ground on a television camera tube during the scanning and transmission of the picture.

*U. S. No. 2,931,858.* J. H. Hammond, Jr. and E. L. Chaffee. Iss. 4/5/60. App. 10/3/55. Assign. J. H. Hammond, Jr.

*Television Reconnaissance System.* A system for transmitting observations of the ground from an airplane by means of a television camera having a moving shutter that keeps the image stationary on the tube while it is being transmitted to the ground.

*U. S. No. 2,931,963.* G. P. Wilson. Iss. 4/5/60. App. 2/4/57. Assign. Bell & Howell Co.

*Linear Induction Motor Servosystem for Recording Oscillograph.* A recorder having a stylus that is carried across the record medium by a linear induction motor system whose quadrature field is controlled by the difference between the signal and the position of the stylus.

*U. S. No. 2,934,263.* H. W. Patnode. Iss. 4/26/60. App. 12/27/56. Assign. Gulf Research & Development Co.

*Electromechanical Scanning Apparatus.* A device for detecting alignments on a map drawn with conducing ink and having a pair of electrodes that are moved to scan the map and connected to a circuit that counts the number of times the electrode circuit is completed by a line on the map, the process being repeated with the map in various azimuthal orientations and the counts compared.

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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

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# REVIEWS

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International Symposium on Electronic Distance-Measuring Techniques—Proceedings edited by C. A. Whitten and Erwin Schmid, *Journal of Geophysical Research*, Vol. 65, No. 2, 1960, pp. 385–528.

The proceedings of the symposium held in Washington, D. C, May 5–12, 1959, under the auspices of the International Association of Geodesy, are reported in the first 144 pages of the February 1960 issue of the Journal. Some of the papers, because of space limitations, appear in condensation or in abstract; others, because of previous publication, have been omitted. The material covered is concerned primarily with the theory, technical details, applications and error analyses of the various distance measuring systems in use or proposed for use either in geodetic work or in establishing horizontal control for mapping or geophysical operations.

Since all the systems in one way or another involve the velocity of propagation of electromagnetic waves, quite appropriately the phenomena affecting such propagation are given ample consideration in many of the papers. To the extent that many employ phase comparison devices, these systems are alike in basic principle. The differences are in the type of carrier modulation, relative disposition of transmitter and receiver, and the manner in which phase information is displayed.

Early developments culminated in the Geodimeter, an electro-optical system employing Kerr cell light modulation. The system easily attains first order accuracy, makes tape distance measurement quite superfluous, and avoids the objectionable ground reflections of purely electronic systems. Limited range (intervisibility) and considerable weight are the more serious disadvantages.

Seven papers are devoted to the Tellurometer, an all-electronic system introduced about three years ago. Although of somewhat lower accuracy than the long range type Geodimeter, the Tellurometer is lighter in weight, less expensive, and less susceptible to weather conditions. The uninitiated will

be disappointed to find no discussion of the theoretical aspects of this important system; nevertheless a few references are given. The system is undergoing extensive and intensive tests especially by those who plan to use it in undeveloped and inaccessible regions.

Despite the advances in electronic distance measuring, the system of highest accuracy ($1:10^7$) is the optical Väisälä light interference comparator introduced some thirty years ago and reported in separate papers by W. A. Heiskanen and T. Honkasalo. The I.U.G.G. in 1954 and the U.N. Regional Cartographic Conference for Asia in 1955 recommended this system for certain standard base-line measurements.

In addition to bringing the reader up to date on Shoran, Hiran, Loran, LoRAC, Decca and Raydist systems, the experimental results reported may be of assistance to those trying to decide on a suitable position fixing system.

The least squares adjustment of trilateration nets, in general, employs the observation equation method rather than the condition equation method traditionally used in the adjustment of triangulation networks.

Electronic distance measuring will play an important role in the future of geodesy. The proceedings therefore would seem to be essential reading for geodesists. Geophysicists, cartographers and also the layman will want to read them to keep abreast of the trends in electronic distance measuring systems.

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A Suggested Method for Measuring Tape Modulation Noise, J. J. Davidson, *Journal of the Audio Engineering Society*, Vol. 8, 1960, pp. 23–28.

Modulation noise is defined as "noise which exists only in the presence of a signal and is a function of the instantaneous amplitude of the recorded signal" (*Proc. I.R.E.*, v. 41, pp. 508–512, 1953, and GEOPHYSICS, v. 23, p. 928). In the case of magnetic tapes, its cause is generally attributed to the inhomogeneous composition of the oxide coating.

To measure modulation noise, the author proposes to record the same signal simultaneously on two magnetic tracks. The output of each track, then, will contain the signal plus noise, which of course is random. Subtracting one output from the other cancels the signals, leaving only the noise. With reasonable care, the noise aggregate will consist mainly of the modulation noise, the other components being lower by at least one order of magnitude.

The remainder of the paper treats the difficulties associated with the above technique. The author states: "Anyone who has worked with the problem of cancelling two supposedly identical signals can attest to the fact that, no matter how identical the signals are supposed to be, they never seem to be identical enough."

Inasmuch as the above technique has been proposed at various times for the purpose of rejecting the "singing" frequencies in offshore records, this reviewer believes it may be of interest to single out one of the critical factors discussed by the author and to present it in this more familiar context.

To eliminate a singing frequency, $f$, we proceed as in the second paragraph above, remembering that, prior to mixing the outputs, one of the heads must be translated in time by $\tau=\frac{1}{2}f^{-1}$ seconds. We will assume the two outputs to be identical in amplitude and phase, leaving only the error in translating the head, namely, $\Delta\tau$. We have, then, $\sin \omega t$ for one output and $\sin \omega(t+\tau+\Delta\tau)$ for the other. After mixing, the residue, $R$, becomes $R=(1-\cos \omega\Delta\tau) \sin \omega t-(\sin \omega\Delta\tau) \cos \omega t$. Since for $\Delta\tau$ sufficiently small, $\sin \omega\Delta\tau \gg (1-\cos \omega\Delta\tau)$, and since $\sin \omega\Delta\tau=\omega\Delta\tau$ approximately, we have (ignoring the sign) $R=\omega\Delta\tau \cos \omega t$. Assuming, now, that a rejection of 40 db (100:1) is required and that the singing frequency is 32 cps, it is clear that the tolerable error in moving the head is only 50 microseconds.

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*Wave Propagation and Group Velocity*, L. Brillouin, Academic Press, New York and London, 1960, xi+154 pp., $6.00.

This book, written by the author of *Wave Propagation in Periodic Structures*, should interest the majority of theoretically minded geophysicists concerned with the various aspects of wave propagation in media having dispersive or absorptive characteristics.

The material contained in this book is rather old since, as mentioned in the author's foreword, it is "a systematic presentation of [the] original papers which are rather difficult to find nowadays." These papers were written by A. Sommerfeld and L. Brillouin over a period extending from 1914 to 1936. The reviewer shares the author's opinion, again expressed in the foreword, that this book "will be helpful to many readers and save them time and trouble, especially the trouble of recomputing and rediscovering many important features of the general theory."

No attempt will be made to abstract the book because it is felt that theoretical treatments of this kind should be viewed in their entirety to guard against the dangers inherent in the generalization of results acquired in a detailed investigation of a specific problem. The titles of the six chapters of this book supply adequate information concerning the specific investigations contained therein: I. Introduction; II. About the Propagation of Light in Dispersive Media by A. Sommerfeld; III. About the Propagation of Light in Dispersive Media by L. Brillouin; IV. Propagation of Electromagnetic Waves in Material Media; V. (Electromagnetic) Wave Propagation in a Dispersive Dielectric; and VI. Waves in Wave Guides and Other Examples.

The primary interest of this book for practicing theoretical geophysicists lies, in the reviewer's opinion, in its clear presentation of the application of advanced mathematical techniques of complex integration to the detailed investigation of signal propagation through dispersive and absorptive media. Saddle points integration is used repeatedly and an interesting comparison between it and the method of stationary phase is made at the end of chapter III. Numerous detailed discussions of the physical meaning associated with the results derived from the deformation of the path of integration constitute illuminating examples of the potentiality of the complex integration methods in the detailed investigation of physical problems.

In addition, the important concepts of the various velocities which may be defined in the propagation of waves through material media are analyzed in great detail. Anyone interested in gaining a more precise understanding of the exact relationship and distinction between phase velocity, group velocity, signal velocity, and velocity of energy transport involved in the propagation of signals of limited duration through a material medium should make the effort required to understand this book. Other interesting information concerning forerunners and their characteristics will be gained at no extra cost.

The reviewer has found several minor printing errors in the formulae. These errors may increase slightly the difficulty of following the analysis in its minute details, but none is serious enough to justify questioning the validity of the analysis and the serious reader should be able to make the necessary corrections. In view of the large number of complex formulae present in this book, it is felt that the author and publisher may be excused for these imperfections.

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On the Propagation of Transient Elastic Waves, Shozaburo Nagumo, *Report No. 184, Geological Survey of Japan*, Hisamoto-chō, Kawasaki-shi, Japan, 1960.

This report of 50 pages is on the theory of 2-dimensional pulse problems. It is divided into 4 chapters. It is a valuable paper in a rather long list of publications in this field starting with Lamb and continuing on to Nakano, Lapwood, Takeuchi and Kobayashi, Garvin, and de Hoop, to mention a few citations in the author's list of 27 papers and books.

The use of the Laplace transform (following Cagniard) and of the Fourier transform also (following Sneddon) gives an elegant organization to the theory. The simplicity that can be achieved by

this double transform method goes toward making the theory deductive. The only deductive gap that is still essential appears in the transition from the elasticity equations of motion in terms of displacements to the potential equations. No one doubts the validity of this transition, but it is not unique so, at a late stage in the work, an appeal to a "uniqueness theorem" is always necessary.

The first chapter treats the surface source for the 2-dimensional half-space. Both the concentrated and extended sources are treated. Probably a reference to the work of Miller and Pursey (*Proc. Roy. Soc. Lond.* (A), 223, p. 521–541 (1954)) should have been included here.

The second chapter treats the buried line-source problem. This is a discussion naturally associated with that of chapter one.

The third chapter treats the two semi-infinite fluids with the source in one side and a plane of separation. Included is a rather complete graphical presentation of numerical results with a discussion of the physical picture of the processes—a very valuable discussion for the physicist interested in getting a correct understanding of the processes.

The fourth chapter treats a diffraction problem in an infinite fluid with a line source and a barrier strip. Here the mathematical result appears correct and the treatment very neat. However, the illustration (Figure 33) and the words that interpret the result appear to me to be only of partial validity. It appears to me that the diffraction must appear in what the author calls the "refraction region" and also in the "reflection region" (Figure 30). The "fronts" in question are hidden in equations (4.23) and (4.25) in the expressions for $t_1$ and $t_2$ and will emerge if a sufficient number of differentiations of the potentials are carried out.

The author introduces the idea of an "incomplete reflection." One cannot doubt the validity of this analysis of the pulse field. The splitting of the pulse field by an inverse superposition process may be done in an infinitude of ways. The way used here assigns a basic reference position to the reflection from the complete plane. Perhaps this will be useful for the generalization of the theory to reflection from non-plane surfaces.

There are a few minor misprints that will not be misleading to most readers.

The paper is a clearly written account for geophysicists, physicists, and applied mathematicians. Workers interested in 2-dimensional models should find this work valuable. The simplicity and directness of the treatment is not only beautiful—it is useful in that it suggests probably fruitful directions for generalizations that can bring our understanding closer to actual cases.

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*Introduction to Geophysical Prospecting*, Milton B. Dobrin, McGraw-Hill Book Company, Inc., New York, 1960, ix+446 pp., $9.50.

Originally published in 1952, this book now appears as a second edition with revised content. As stated in the preface to the second edition, the author has attempted to provide "a résumé . . . of recent advances in the various geophysical techniques along with references to the most useful and accessible papers." He also states that "The chapters on seismic prospecting, particularly those on instrumentation and on reflection and refraction techniques, have been substantially enlarged to provide proper coverage of new developments." In addition, there has been added a chapter on coordination of geology and geophysics. To accommodate the additional material, chapters on well logging, radio position locating, and geophysical research have been deleted.

On the whole, the content of the review of the first edition published in Geophysics (vol. 17, p. 966–967, 1952) is applicable to the present edition. Changes in text material in the second edition have done little or nothing to change the tenor and emphasis of the book. A feeling of increased emphasis on seismograph techniques is, nevertheless, obtained largely by reason of the rearrangement of chapters in the second edition.

The chapter entitled "Seismic Instruments and Seismic Surveys" has been increased in length from 17 to 29 pages, the chapter entitled "The Seismic Refraction Method" has been increased from

28 to 36 pages, and the chapter entitled "The Seismic Reflection Method" has been increased from 40 to 43 pages. A detailed analysis of the changes discloses that 5½ pages of text on air shooting (the Poulter method) have been eliminated from the reflection chapter, to be replaced by a ½-page reference in the first-mentioned chapter. The remainder of the increase in the instruments and surveys chapter is represented by a moderate amount of text and a number of pictures dealing with magnetic tape recording apparatus. A short section on weight dropping has also been added. Pictures of seismometers have been replaced with those of newer instruments. On the other hand, the section on seismic operations in water-covered areas has been slightly rewritten and has had added a full-page diagrammatical illustration of water operations which, unfortunately, is at least six years out of date. The description of marine seismic operations is, in essence, unchanged from the first edition and is descriptive of operations as they existed prior to 1949. All of the radical revisions in water operation that have taken place from 1950 to date have been completely ignored.

The chapter on refraction shooting has been expanded through the addition of material on the broadside technique and through the elaboration of the delay-time method.

Newly introduced in the chapter on reflection prospecting are record-section presentation systems and a small amount of material on pattern shooting.

Chapters on methods other than seismic have been changed only slightly. It is satisfying, however, to note that the question left hanging in the first edition of how the Worden gravimeter achieves its temperature compensation is answered in the second edition.

By the addition of a chapter on interpretation and geologic coordination of reflection data, Dr. Dobrin has made a significant improvement in the text. It is to be hoped that his earnest, well-documented plea for sensible cooperation between geologists and geophysicists in achieving their common goal will be heeded. Certainly all oil finders, particularly those in exploration management, should read and follow this chapter.

Other than the addition of this significant chapter, the changes in the text between the first and second editions appear to be perfunctory. With respect to field operations and geophysical practice, the viewpoint expressed in those changes is parochial. Examples of new records and record sections to replace some of the older material or to illustrate new text material are almost all taken from western Canada. Total lack of familiarity with modern offshore operations is apparent in the lack of mention of pressure-sensitive detectors, buoyant cables and "L" spreads. From the text it would appear that the only problem facing the offshore seismologist is that of bubble pulses. This problem has, of course, long been solved. Of "singing," ocean-bottom multiples, and other water-borne "noise" no mention is made.

It appears that with respect to some of the newer techniques, the author has been content to rely upon advertising claims for an evaluation of methods and equipment. Such reliance is implicit in some discussions of instrumentation and is present on pages 119–120 in the discussion of one-receiver vs two-receiver velocity logging techniques. The author accepts at face value the contention that the two-receiver logs require fewer check shots to calibrate them than do the one-receiver logs. This contention has been amply disproved in the experience of at least one velocity surveying association.

Revision of tables of numerical values in line with more recent data probably should have been undertaken. For example, the tabulation of rock velocities given in the book is still the one originally printed in Birch's *Handbook of Physical Constants*, 1942.

The high quality of the discussion of underlying physical principles presented in the original edition is retained and even augmented. As a text for teaching the general aspects and principles of geophysical exploration, Dr. Dobrin's book retains its high worth. On the other hand, the lesser quality of the writing on field instrumentation and techniques noted by the reviewer of the first edition is accentuated in the second edition.

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Mass Areal Seismic Surveying in the Carpathians, V. D. Zav'yalov, *Petroleum Geology*, Vol. 2, pp. 1044–1050, 1958 (English edition published 1960).

While this paper is principally concerned with a local surveying problem in Russia, it represents the first publication in English on the method of "mass areal seismic surveying." From the discussion it appears that Russian geophysicists have adopted a saturation, spot-shooting technique for use in heavily broken up, high-dip areas. They apparently give up continuous profiling for saturation coverage of individual locations. By so doing they claim to have successfully mapped a number of complex areas.

Among the advantages of the mass areal system is relative freedom of choice of surface areas to be worked. Thus, in mountainous areas the locations chosen for intensive coverage are the accessible flat spots. Disadvantages pointed out by the author are insufficient accuracy of dip determinations and some lost facility to distinguish spurious arrivals. Both of these difficulties presumably arise from lack of continuous coverage. The first of these difficulties is in part overcome by increasing the number of dip determinations made at each location.

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*Inventions, Patents, and Their Management*, Alf K. Berle and L. Sprague de Camp, D. Van Nostrand Company, Inc., Princeton, New Jersey, 1959, ix+602 pp., $12.50.

Berle and de Camp have written the present book as a complete updating and revision of their former work, *Inventions and Their Management*, published by International Textbook Company. Four editions of the original book appeared between 1937 and 1954. It might appear that the present work should more properly be considered a fifth edition of the original. Retitling as a new book may simply be attributable to the change in publisher. In any event, the differences between the present volume and its predecessors are quite extensive. Changes in patent law in the United States and elsewhere and availability of new cases and examples since 1954 have made extensive revision mandatory.

*Inventions, Patents, and Their Management* examines the field of patents and, to a limited extent, the peripheral subjects of trademarks, copyrights, trade secrets, and unfair competition from the viewpoint of the independent inventor who seeks to exploit his inventions for maximum gain. In 532 pages of text, Berle and de Camp call upon their extensive experience in inventor training and patent counselling to produce a comprehensive, readable treatise on the strategy and tactics of inventing and profiting from one's invention. Both authors are primarily engineers and administrators, Berle having been graduated from M.I.T. and de Camp from CalTech. Legal aspects of patent management are, accordingly, treated largely from a layman's viewpoint. General principles of law are laid out in considerable detail but in lay language. The reader is consistently advised to consult a competent lawyer when legal or contractual problems arise.

In keeping with the aim of the book, which is to aid inventors in inventing and in exploiting their inventions, the chapters on patent prosecution are perfunctory. The inventor is cautioned to place the management of patent prosecution in the hands of a competent patent attorney. Enough material is, however, presented to enable the inventor to understand the process of prosecution. He is also urged not only to cooperate fully with his attorney by disclosing all important facts, but to keep himself continually aware of the course of prosecution so that he may fruitfully participate in it. The inventor is also given suggestions on how to decide whether or not his attorney is competent and conscientious.

Examples of proper and improper management of inventions, good and bad patents, court decisions, nonpatentable but well-exploited inventions, etc., abound. If any one class of examples can be said to characterize the book, it is that class of examples which illustrates the financial reward which an inventor can reasonably expect to obtain from an invention.

Much time and effort of all the major industrial corporations of the United States could be saved if every independent inventor were required to read and understand this volume before being permitted to approach a company with a view to marketing his invention. Any inventor who has read and understood *Inventions, Patents, and Their Management* would be unlikely to fall into the nearly universal pitfalls of valuing his invention, whatever it is, at "one million dollars," of being unwilling to disclose enough information to enable the prospective purchaser to understand and evaluate the invention, and of stating that he is the victim of a conspiracy to suppress a world-shaking advance. Clearly set forth in this book is a realistic appraisal of the relative contributions, risks, and values of the invention, the capitalization of its exploitation, and the marketing and sales organization required for commercial success. Unfortunately, the people who most need to read this book will probably conclude either that they already know more than the book contains or that the book is part of a universal conspiracy to deprive them of their "rights."

As is expected in a book which has passed through many editions and has been used for teaching, there are no readily discernible errors in the text. As a matter of fact, this reviewer noted that although one specific topic, the time limit for broadening claims by reissue, is expressly or indirectly stated from 8 to 10 times in various places in the text, it is everywhere correct. Such consistency is evidence of very careful editing since the particular time limit involved has been twice changed in recent years.

If criticism is to be leveled at the work, it must be by reason of a very common failing of experts. Although attempts are consistently made to avoid references to information not ordinarily in possession of the layman, nevertheless such references occur from time to time. In particular, technical patent terminology is rather freely used without adequate preamble. A 27-page glossary, which follows the excellent bibliography, tends to ameliorate this defect. References to relatively obscure facets of income-tax law and rulings, however, cannot be cleared up by recourse to the glossary.

Certainly every independent inventor should study this book carefully. People who have to deal with independent inventors or even with employee inventors in the course of their business activities should also be familiar with the book's contents. Even a casual reader will find the book quite entertaining and full of delectable tidbits of information.

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Dielectric Constant and Electrical Resistivity of Natural-State Cores, G. V. Keller and P. H. Licastro, *Geological Survey Bulletin No. 1052-H*, U. S. Government Printing Office, Washington, D. C. (1959).

Dielectric constant and resistivity data are presented for twenty-seven cores from the Morrison Formation in the Uravan mineral belt of the Colorado Plateau. The measurements were made over a frequency range of 50 to $30 \times 10^6$ cps. The drilling was done with air and oil-base mud to preserve the original water characteristics as much as possible.

In several cases large dispersion is evident in the data. The authors interpret this in terms of a distribution of relaxators using a Wagner-Yager[1,2] technique to evaluate several parameters in the equations[1] that describe the effect. In the example given, the data seem to fit this model fairly well.

The effects of electrode polarization are ruled out by the authors mostly on the basis that the static dielectric constant estimated from the measurements is smaller than the value that generally results from this effect. It is probably a mistake to rule out the effects of electrode impedances completely as, for example, very thin impurity layers on the electrode surface will appear as an apparent reduction in the polarization capacitance and, consequently, the core data will be perturbed at higher frequencies than one would expect from simple polarization effects.

A good semi-quantitative argument is presented for the possibility of local charge accumulation,

[1] Wagner, K. W., *Annalen der Physik*, 40, 817 (1913).
[2] Yager, W. A., *Physics*, 7, 434 (1936).

due to salt filtering, causing the dielectric dispersion seen at low frequencies. This is probably a real effect in cores that contain clay minerals. The possibility of polarization effects at the rock-water interfaces was not considered. Also unconsidered were the possibilities of high values of the static dielectric constant resulting from Maxwell-Wagner effects in a composite of conducting and non-conducting dielectric materials.

DAVID A. LOWITZ
Gulf Research & Development Company
Harmarville, Pennsylvania

*The Theory of Space Time and Gravitation*, V. Fock, translated from the Russian by N. Kemmer, Pergamon Press, New York, 1959, xviii+411 pp., $15.00.

Students of relativity theory are well aware of Fock's important contributions to the subject, but until the appearance of this book very little of his work was available in English. The present work consists of seven chapters, the first four of which constitute a graduate level text on the standard theory and the remaining chapters an account of the author's contributions. Even in the classical material the author has something new to say on almost every topic. The prospective reader is warned that the book is not for the novice; some prior knowledge of the subject is assumed. The book will be only of indirect interest to the exploration geophysicist but can be strongly commended to theoretical physicists.

H. KAUFMAN
McGill University
Montreal, Canada

*Physical Geography*, Arthur N. Strahler, John Wiley & Sons, Inc., New York, 1960 (Second Edition), vii+534 pp., $7.50.

An introductory college text on physical geography. Topic coverage is broad, descriptive, explanatory, and non-mathematical. The book is handsomely done, and copiously illustrated. The major subdivisions are, The Earth as a Globe, The Weather Elements, Climate and Soil, and Land Forms. The last subdivision occupies about half the book.

F. G. BLAKE
California Research Corporation
La Habra, California

## PUBLICATIONS RECEIVED

### BOOKS

*The Nature of Science*, by David Greenwood, Philosophical Library, Inc., New York, $3.75.

*The Story of Chemistry*, by George Lockemann, Philosophical Library, Inc., New York, $4.75.

*Geology of the Industrial Rocks and Minerals*, by Robert L. Bates, Harper and Brothers, New York, $10.00.

*Statistical Theory of Signal Detection*, by Carl W. Helstrom, Pergamon Press, New York, $9.50.

*Principles of Geochemical Prospecting*, by I. I. Ginzburg, Pergamon Press, New York, $11.50.

*Lithofacies Maps*—(An Atlas of U. S. & Southern Canada), by L. L. Sloss, E. C. Dapples and W. C. Krumbein, John Wiley & Sons, Inc., New York, $5.50.

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*Nomography*, 2nd Edition, by Alexander S. Levens, John Wiley & Sons, Inc., New York, $8.50.

*The Analysis of Variance*, by Henry Scheffe, John Wiley & Sons, Inc., New York, $14.00.

*The First Big Oil Hunt—Venezuela*, by Ralph Arnold, George A. Macready, and Thomas Banington, Vantage Press, Inc., New York, $10.00.

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*Methods in Geochemistry*, edited by A. A. Smales and L. R. Wagner, Interscience Publishers, New York, $13.50.

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*Boletin de la Associacion Mexicana de Geologos*, v. 11, nos. 11 & 12 (November & December, 1959)

*Bulletin (Izvestiya)*, nos. 3 & 4 (March & April, 1960)

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*Economic Geology*, v. 55, nos. 3 & 4 (May, June & July, 1960)

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*Geoloski Glasnik* (1958)

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*Journal of Geomagnetism and Geoelectricity*, v. 11, n. 3 (1960)

*Journal of Geophysical Research*, v. 65, nos. 5 & 6 (May & June, 1960)

*Journal of Petroleum Technology*, v. 12, nos. 5 & 6 (May & June, 1960)

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*Mining Engineering*, v. 12, nos. 4, 5, & 6 (April, May & June, 1960)

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*Proceedings of the Cambridge Philosophical Society*, v. 56, n. 2 (April, 1960)

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*Zeitschrift für Geophysik*, v. 25, n. 5 (1959)

# LETTERS TO THE EDITOR

## NON-TERRESTRIAL ORIGIN OF THE TEKTITES

J. HOCHMAN AND JOHN A. O'KEEFE*

In several recent papers the chemical constitution of the tektites† has been compared with that of terrestrial rocks, both igneous and sedimentary. The impression might be obtained from these papers that there are no systematic chemical differences between tektites and terrestrial rocks. In fact, however, there is a systematic tendency for the tektites to be deficient in volatile materials. Friedman has found that the gas content of tektites is less than 1 ppm. He also finds that the water content is lower than that of nearly all terrestrial materials; it is nearly always less than .02 percent. In the same way Mueller first pointed out that the alkalies are systematically low in the tektites as compared to the oxides of divalent metals. Loewinson-Lessing is stated to have found a systematic chemical difference depending both on the acidity coefficient and the ratio of monovalent to divalent oxides.

The question of systematic chemical differences between the tektites and terrestrial rocks is important because of the possible light which it may shed on theories that the tektites have come from other bodies such as the Moon. To re-emphasize this point, the criterion worked out by Mueller has been used. Mueller employed the ratio

$$\frac{FeO + MgO}{Na_2O + K_2O}$$

which we shall designate as $m$. Mueller pointed out that the ratio $m$ served to distinguish the tektites from the igneous rocks. We found, in accordance with Loewinson-Lessing, that $m$ discriminates more effectively if it is plotted as a function of silica.

As source material for the terrestrial rock, Clarke's (7) compilation was used. Figure 1 shows all analyses in Clarke except certain iron ores and dolomites having more than 25 percent FeO or MgO, and $SiO_2$ less than 60 percent. These rocks obviously have nothing to do with the tektites. In addition, eight igneous analyses with silica less than 60 percent and three sedimentary analyses fell off the plot at the top; the least value of $m$ in this group was 4.84; the next was 5.7.

The tektite analyses include all analyses from the paper of Barnes, and therefore include several new finds not available to Mueller or Loewinson-Lessing.

* Theoretical Division, Goddard Space Flight, Center National Aeronatuics and Space Administration, Washington, D. C.

† A glassy rounded rock of uncertain but not volcanic origin.

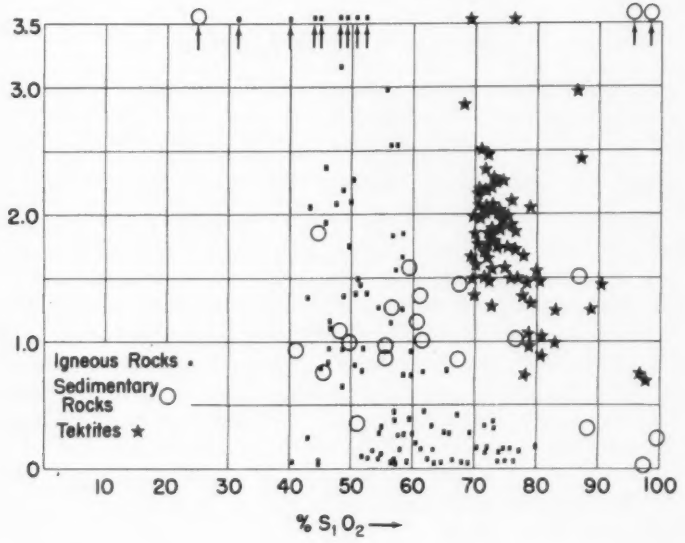


FIG. 1

In Figure 1, igneous rocks are plotted as black squares, sedimentary rocks as circles, and tektites as stars.

It will be seen at once that there is a complete, clear separation between the tektites and the igneous rocks, with no overlap whatever. It appears that the tektites are not derived from terrestrial igneous rocks.

There is some overlap between the tektites and the sedimentary rocks. Three out of twenty sedimentary analyses fall in the region of the tektites; however, the majority fall on low-silica side. This agrees with previous studies, which show that the majority of sedimentary rocks are shales. It appears that the tektites are not a fair sample of the sedimentary rocks.

We conclude that the tektites are not a fair sample of terrestrial rocks; and in particular they are not derived from terrestrial igneous rocks.

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# SUMMATION OF AN INFINITE SERIES ARISING IN THE THEORY OF SUB-SURFACE ELECTRICAL MEASUREMENTS

DR. H. KAUFMAN*

In his work on sub-surface electrical measurements Buckner (1954) makes extensive use of a series defined by:

$$G_A(x) = \sum_{n=1}^{\infty} \frac{A^{2n}}{x + 2n}, \qquad |A| < 1.$$

The purpose of this note is to:

(a) derive a simple closed form for $G_A(x)$,
(b) obtain a recursion formula for this function,
(c) remove the restriction that the material above and below the intermediate bed be of the same resistivity.

The present derivation applies to any case where the electrode arrays intersect at right angles extensive horizontal beds (Buckner) or form traverses on a surface perpendicular to vertically dipping beds (Log $n$).

(a) With $A^2 = P$, $x/2 = k$, we have

$$2G_A(x) = \sum_{n=1}^{\infty} \frac{P^n}{n + k} \equiv R(k).$$

Consider the series

$$S(y) = \sum_{n=1}^{\infty} P^n y^{n+k-1} = y^{k-1} \cdot \frac{Py}{1 - Py}, \qquad |Py| < 1$$

$$= \frac{Py^k}{1 - Py}.$$

Then

$$\int_0^z S(y)dy = \sum_{n=1}^{\infty} \frac{P^n z^{n+k}}{n + k} = \int_0^z \frac{Py^k dy}{1 - Py}, \qquad |Pz| < 1,$$

so that

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$$R(k) = \int_0^1 \frac{Py^k dy}{1 - Py}, \qquad (k > -1)$$

$$= \int_0^1 \frac{y^k dy}{\beta - y}$$

$$= \int_{\beta-1}^{\beta} \frac{(\beta - u)^k}{u} du$$

where $\beta = 1/P$.

The latter two expressions provide simple closed forms for $R(k)$ (and hence $G_A(x)$).

For example

$$G_A(0) = \frac{1}{2} \int_{\beta-1}^{\beta} \frac{du}{u} = \frac{1}{2} \ln \frac{1}{1 - A^2}$$

$$G_A(2) = \frac{1}{2} \int_{\beta-1}^{\beta} \frac{\beta - u}{u} du = \frac{1}{2} \left[ \frac{1}{A^2} \ln \frac{1}{1 - A^2} - 1 \right].$$

It is evident that the integrations can be explicitly carried out if $k$ is a non-negative integer. This is also true if $k$ is any rational number ($> -1$). Thus setting $k = p/q$, and substituting $y = v^q$,

$$R(p/q) = q \int_0^1 \frac{v^{p+q-1} dv}{\beta - v^q}$$

so that the integrand is a rational function and can be integrated by partial fraction decomposition.

(b) If $k$ is replaced by $k+1$, we have

$$R(k+1) = \int_{\beta-1}^{\beta} \frac{(\beta - u)^{k+1}}{u} du.$$

$$= \int_{\beta-1}^{\beta} \frac{(\beta - u)^k}{u} \cdot (\beta - u) du$$

$$= \beta R(k) - \int_{\beta-1}^{\beta} (\beta - u)^k du.$$

The latter integral exists for $k > -1$, and equals $1/(k+1)$. We thus obtain the recursion relation

$$R(k+1) = \beta R(k) - \frac{1}{k+1}$$

or equivalently

$$G_A(x+2) = \left(\frac{1}{A^2}\right) G_A(x) - \frac{1}{x+2}, \qquad x > -2.$$

This relation may be of use in computation, for if $G_A(x)$ is computed for values of $x$ in the range $-2 < x \leq 0$, it can be evaluated for any other $x > 0$ (alternatively, if computed for $0 \leq x < 2$, it can be found for any other $x > 0$ and for $-2 < x < 0$).

(c) If the resistivities of the material above and below the intermediate bed are not the same, the basic series as given by Buckner (p. 301, equation (10)) is

$$\sum_{n=0}^{\infty} \frac{(-1)^n A^n B^{n+1}}{2n(b-a) + 2b - z}$$

which becomes, with $b-a=1$, and $x=2(a+1)-z$,

$$\frac{B}{x} + B \sum_{n=1}^{\infty} \frac{(-1)^n A^n B^n}{x + 2n}$$

where

$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}, \qquad B = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2}.$$

$\rho$ = resistivity of intermediate bed
$\rho_1$ = resistivity of material below this bed
$\rho_3$ = resistivity of material above the bed.

Replacing $B$ by $-C$,

$$\sum_{n=1}^{\infty} \frac{(-1)^n A^n B^n}{x + 2n} = \sum_{n=1}^{\infty} \frac{(AC)^n}{x + 2n}.$$

This is the same as the series for $G_A(x)$ with $A^2$ replaced by $AC$, and all the preceding remarks apply to this less restrictive case.

It may be noted that in a closely related paper, Log *n* (1954, p. 747, equation (12)) replaces the $G_A(x)$ series (including the $n=0$ term) by an *approximation* involving the exponential integral,

$$Ei(-y) = -\int_y^{\infty} \frac{e^{-t} dt}{t}.$$

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Logn, Ö., 1954, Mapping nearly vertical discontinuities by earth resistivities: Geophysics, v. 19, p. 739–760.

# HORIZONTAL SURVEYING ACCURACY REQUIRED FOR GRAVITY METER PROJECTS

L. F. IVANHOE*

ABSTRACT

The paper points out the limits in accuracy of gravity meter data in areas of steep regional gradients due to errors in the locations of the gravity stations. A simple formula defines the minimum surveying requirements to obtain any desired accuracy in the gravity values.

The horizontal position of a gravity station must be located with a basic accuracy that corresponds with the final gravity reliability required of the project. The effects of errors in station locations on the final gravity values are very commonly overlooked when planning gravity programs. The plotted positions of the stations must be very reliable to justify precise elevation surveys or terrain corrections. Any errors become critical when magnified by "residual" maps which emphasize anomalous data.

It is essential that each step of the field survey be kept within realistic control limits. It is obvious that the station position does not need to be as precise for a reconnaissance survey, with an acceptable accuracy of 1.0 milligal, as for a detail project where an accuracy of 0.05 milligal is desired. A review of the factors involved in station position vs desired gravity accuracy indicates that routine surveying procedures should be modified for many projects.

The most critical factors in establishing the allowable margin of error for horizontal positions of gravity stations are: (1) The latitude correction and (2) the regional gravity gradient. The predictable latitude correction is usually of less importance since it varies only in the north-south direction and is always less than 1.3 milligals per mile. The latitude correction may either increase or decrease the regional gravity gradient, depending on how the "regional" is oriented. The regional gradient may range from flat to very steep. The gravity map of the Los Angeles, California basin (McCullock, 1957) shows gradients ranging from less than 2.0 to more than 25.0 milligals per mile. In the case of the steeper gradients an error of location of only 200 ft (1/25 mile) results in an error of 1.0 milligal, which would be very prominent on any residual map, and might be misinterpreted.

A simple formula to determine the minimum location accuracy required for a gravity meter station is:

$$\text{Location Accuracy (miles)} = \frac{\text{Gravity Required (milligals)}}{\text{Regional Gravity} + \text{Latitude Correction (/mile)}}.$$

* Bakersfield, California.

Example:

$$\text{Survey Accuracy (miles)} = \frac{0.1 \text{ mg}}{8 + 1.2 \text{ mg/mile}} = 0.011 \text{ mile} = 60 \text{ feet.}$$

The latitude corrections can be obtained from commonly available tables (Nettleton, 1940), but the regional gravity must either be obtained from existing reconnaissance gravity maps or be estimated. Steep gravity gradients should be anticipated near mountains with basement rocks, but are less common over broad sedimentary basins. Regional gravity maps, from any source, are great aids in establishing realistic surveying standards for detail surveys.

It is apparent that in areas with steep gravity gradients and unfavorable terrain, it may be very difficult to locate the gravity stations with sufficient accuracy to justify highly detailed field or office techniques. Any attempt to make refined geological interpretations of gravity data in such cases may be unjustified and misleading. Undue emphasis should not be given to isolated gravity anomalies on residual maps in areas of steep gravity gradients until the accuracy of the station locations has been checked.

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McCulloch, T. H., 1957, Simple bouguer gravity and generalized geologic map of the northwestern part of the Los Angeles Basin, California: U.S.G.S. Map GP 149.

## ERRATA FOR "PLANE COMPRESSIONAL VOIGT WAVES"

(GEOPHYSICS v. 25, p. 483)

Page 496, equation (39), left member should read $a_n$.

Pages 488 and 489, equations (9) to (16), the symbol $\sigma$ (sigma) should be in bold type to indicate that it represents a Laplace transform.

Page 502, equation (56), left member should read $\mathbf{v}_r(r,s)$.

FRANCIS COLLINS

HOWARD COBB

HOWARD COBB received an A.B. degree in mathematics from Drake University in 1933 and an M.S. degree in physics from the University of Oklahoma in 1935. He worked for Mott-Smith Corporation as gravity meter party chief until 1943 when he joined The Atlantic Refining Company. He is Gravity Meter Supervisor for The Atlantic Refining Company. He has also made studies on the uses of electronic computers in oil exploration. He is a member of the Society of Exploration Geophysicists and of The American Association of Petroleum Geologists.

PAUL A. ELKINS

PAUL A. ELKINS was born in Rosenberg, Texas. He joined Torsion Balance Exploration Company in 1933. From 1939 to the present he has been with Gravity Meter Exploration Company. Most of his experience has been in the Gulf Coast area of Texas and Louisiana. Mr. Elkins has also had ten years experience in Central and South America.

ALEX FROSCH

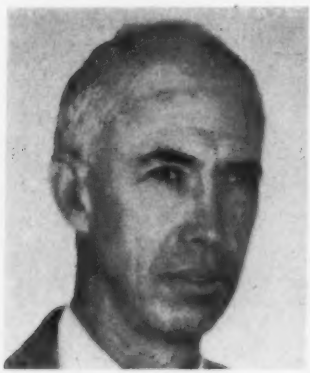
ALEX FROSCH is a native of Houston, Texas, and a graduate of The Rice Institute. He has been occupied in prospecting and well logging research with the Humble Oil & Refining Company since 1930 in electrical, gravity, radioactivity, seismic and magnetic methods.

He is a member of the Society of Exploration Geophysicists, the American Geophysical Union, The Institute of Radio Engineers, and the American Physical Society.

JOHN H. HEALY graduated from Massachusetts Institute of Technology in 1951 with a degree in geology. He then worked for the U. S. Air Force at the Air Force Cambridge Research Center until 1954, when he went to work for the Chevron Oil Company on a seismic crew. In 1956 he was employed by the California Institute of Technology and received his master's degree in geology in 1957. He is currently working toward a Ph.D. in geophysics.

LYNN G. HOWELL, a native of East Texas, was an undergraduate at the University of Texas and later received a Ph.D. at the California Institute of Technology. In physics his researches have been concerned with the kinetics of colloidal particles and measurements of cosmic rays in airplanes. Since leaving Caltech he has been engaged in geophysical research with the Humble Oil & Refining Company in Houston where he has worked on gravity meter instrumentation, surface radioactivity, gamma ray well logging, generation and propagation of elastic waves, marine position location, and rock magnetism. During World War II he was on leave in the Washington, D. C. area working on the proximity fuse for large caliber guns gun directors, and the instrumentation for a supersonic wind tunnel in connection with guided missiles. Besides belonging to various scientific societies he is a member of the Houston Philosophical Society and of the Rice Institute Associates.

LYNN G. HOWELL



JOSEPH D. MARTINEZ

JOSEPH D. MARTINEZ received the B.S. degree in electrical engineering from Louisiana State University in 1927. From 1937 to 1941 he was engaged primarily in sales engineering work. In 1941 he was ordered to active duty as a reserve officer and served until 1945 as a captain in the infantry. After the war he was employed as an electrical engineer for two years by the Brown Company of Berlin, New Hampshire. During 1948 and 1949 he maintained an office as a consulting electrical engineer in Baton Rouge, Louisiana.

Mr. Martinez returned to Louisiana State University in 1949 for graduate study and received the M.S. degree in geology in 1952. At this time he joined the geophysics research section of the Humble Oil & Refining Company as a senior research geophysicist. He was a lecturer in geology at the Rice Institute during the academic year 1957–1958, while on leave from the Humble Company. In 1959 he received the Ph.D. degree in geology from Louisiana State University. He is now a senior geologist in the geologic research section of the Humble Company.

Mr. Martinez is a member of the Geological Society of America, the American Association of Petroleum Geologists, the American Geophysical Union, the Society of Economic Paleontologists and Mineralogists, Sigma Xi, and the Houston Geological Society.

TSVI MEIDAV

TSVI MEIDAV was born in 1930 and is a native of Haifa, Israel. In 1951 he came to the U.S. for the purpose of studying. He obtained his B.A. degree in geology from Washington University in 1955, and his M.A. in geophysics in 1956. Following graduation he worked for one year for the Missouri State Geological Survey as a geophysicist and was responsible for the geophysical exploration for ground water and mineral deposits. He returned to Washington University in 1957 to continue his studies towards a Ph.D. in geophysics which he expects to get in 1960. Mr. Meidav is a member of Sigma Xi, Society of Exploration Geophysicists, Seismological Society of America, European Association of Exploration Geophysicists, and the American Geophysical Union.

JOHN L. MERO was graduated from the University of North Dakota in 1952 with a B.S. in Mining Engineering. After three years in the U. S. Army he entered the University of California at Berkeley. In 1957 he received an M.S. in Engineering Science and in 1959 he received a Doctorate in Engineering from the University of California. From 1955 to 1959 he did research in adapting the gamma-ray spectrometer to mineral exploration and to the analyses of uranium and/or thorium ores. From 1957 until the present he has been employed by the Scripps Institution of Oceanography to do research concerning the economic and technical aspects of recovering minerals from the floor of the ocean. In 1960 he received the D. C. Jackling Fellowship to continue research into the analysis of manganese-nickel-cobalt-copper-molybdenum-zinc-vanadium deposits found on the sea floor.

JOHN L. MERO

E. R. NIBLETT is a graduate in Mathematics and Physics from the University of Toronto. He was awarded an M.A. in geophysics from the same institution in 1949 and joined the staff of the Dominion Observatory in 1950 at Ottawa. He obtained leave of absence to study geomagnetism at Cambridge University where he received the Ph.D. degree in 1958. Dr. Niblett is now engaged in research in geomagnetism at the Dominion Observatory. He is a member of the American Geophysical Union and a fellow of the Royal Astronomical Society.

E. R. NIBLETT

CATHERINE SAYN-WITTGENSTEIN

CATHERINE SAYN-WITTGENSTEIN is a B.Sc. graduate in Mathematics from Carleton University, Ottawa, Canada. She joined the Dominion Observatory in 1959 and is at present assisting in research projects of the Division of Geomagnetism.

Biographies of the following authors appear in earlier issues of GEOPHYSICS as follows: L. L. Nettleton, v. 22, p. 474; Frank Press, v. 25, p. 355; Edwin H. Statham, v. 23, p. 380

# SOCIETY ROUND TABLE

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**Mining Geophysics**

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KENNETH L. COOK
PHILLIP G. HALLOF
DON R. MABEY
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ROBERT G. VAN NOSTRAND

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**Publicity**

(To be appointed)

**Business & Finance**

FRANK BROWN ('60), *Chairman*
EDWARD H. WELTSCH ('61)

**Publications**

RICHARD A. GEYER, *Chairman*
W. M. RUST, JR.
MARK K. SMITH, JR.
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**Subcommittee on Translation of Russian Publications**

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W. L. BASHAM
F. G. BLAKE
PIERRIE L. GOUPILLAUD
ROLAND G. HENDERSON
NORMAN H. RICKER
JOSHUA L. SOSKE
S. H. WARD
ISIDORE ZIETZ

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V. U. GAITHER, *Chairman*

**Case Histories**

D. P. CARLTON, *Chairman*

**Geophysical Activity**

H. G. PATRICK, *Chairman*
K. L. COOK
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DR. KUMIJI IIDA
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L. R. TUCKER

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JOSEPH DELERNO, JR.
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R. L. HUFFMAN
C. W. KERNS
C. J. LONG
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HERBERT FERBER
CARL GERDES
G. M. KINTZ
JOHN RICHARDS
C. C. SELLERS, JR.

**Delegates to I.U.G.G.**

JACK OLIVER ('60)
W. A. HEISKANEN ('60)

## LOCAL SECTIONS

**Ark-La-Tex Geophysical Society (6),** Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *sec y-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

**Canadian Society of Exploration Geophysicists (9),** Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
Dr. M. B. Dobrin, *pres.*
P. J. Savage, *vice-pres.*
J. J. Hamilton, *secty.*, Canadian Society of Exploration Geoph., Shell Oil Co. of Canada, Ltd. P.O. Box 880, Calgary, Alta., Canada.
J. G. Goodwin, *treas.*

**Casper Geophysical Society (11),** Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

**Coastal Bend Geophysical Society (24),** Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

**Cochabamba Geophysical Society (23),** Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
R. H. Matthews, *pres.*
Charles W. Hyatt, *v-pres.*
Noel C. Manning, *secty.-treas.*, Geophysical Service Inc., Casilla #1437, Cochabamba, Bolivia.

**Dallas Geophysical Society (4),** Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap, *pres.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

**Denver Geophysical Society (8)**
*Meetings:* Monthly, 1st Monday, 5:30 P.M., dinner at 7:00 P.M. ($3.00), Petroleum Club, Denver.
John C. Hollister, *pres.*
Arthur W. Black, *v.-pres.*
Charles E. McMunn, *secty-treas.* Tower Exploration Inc., P.O. Box 156, Englewood, Colorado.

**Geophysical Society of Edmonton (22),** Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

**Fort Worth Geophysical Society (5)**
O. A. Strange, *pres.*
R. H. Dana, *v.-pres.*
U. A. Rowe, *secty.*
C. H. Thurber, *treas.*, Champlin Oil and Refining Co., Box 9365, Fort Worth, Texas.

**Four Corners Geophysical Society (19),** Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

**Geophysical Society of Houston (2),** Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

**Jackson Geophysical Society (15)**
Joel Macgregor, *pres.*
John Babb, *v-pres.*
Thomas Tillman, *secty.-treas.*, Sun Oil Co., P.O. Box 850, Jackson, Miss.

**Montana Geophysical Society (14),** Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
W. H. Dawson, *pres.*
Phil Hendrick, *1st v-pres.*
F. J. Felice, *2nd v-pres.*
Max Judy, *secty.-treas.*, Sun Oil Co., Box 1896, Billings, Mont.

**New Mexico Geophysical Society (18),** Roswell, N. M., chartered September 18, 1957, officers elected in May.
R. E. Lawson, *pres.*
Delmer M. Woods, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
R. W. Aldrich, *secty.-treas.*, Mobil Oil Co., 714 Petroleum Bldg., Roswell, N.M.

**Geophysical Society of Oklahoma City (10),** Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

**Pacific Coast Section (3),** luncheon ($2.75) Rodger Young Auditorium, Los Angeles.
F. F. Lambrecht, *pres.*
Nolan A. Webb, *v-pres. S.D.*
Fred G. Knight, *v-pres. N.D.*
Tom Slaven, *secty.-treas.*, Western Geophysical Co. of America, 523 W. 6th St., Los Angeles, Calif.

**Permian Basin Geophysical Society (7),** Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
J. E. Clark, *pres.*
E. E. Fickenger, *1st v-pres.*
B. H. Hinton, *2nd v-pres.*
S. T. Mille , *treas.*
L. M. Scofield, *secty.*, Burton Exploration Co. Inc., 4513 W. Storey, Midland, Texas.

**Regina Geophysical Society (22)**
A. C. Armstrong, *pres.*
M. MacIver, *v-pres.*
J. R. Muir, *secty.-treas.*, The California Standard Co., 1836 Smith St., Regina, Saskatchewan, Canada.

**Geophysical Society of South Texas**
J. W. E. Edmonson, *pres.*
P. J. Rudolph, *v-pres.*
Donald W. Jones, *secty.-treas.*, Sun Oil Co., 832 Milam Bldg., San Antonio, Texas.

**Southeastern Geophysical Society (13),** New Orleans, La., chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($2.00), Monteleone Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty.-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

**Southwest Louisiana Geophysical Society (16),** Lafayette, La., chartered January 4, 1956, officers elected in December.
Jack Wallner, *pres.*
Walter Hurt, *1st v-pres.*
Richard Hollenbaugh, *2nd v-pres.*
Ned Pratt, *treas.*
Lucius Geer, *secty.*, Union Oil of California, Box 1224 OCS, Lafayette, La.

**Geophysical Society of Tulsa (1)**
Tulsa, Okla., chartered February 2, 1948, officers elected in May.
T. S. Green, *pres.*
J. E. Hawkins, *1st v-pres.*
K. S. Cressman, *2nd v-pres.*
B. L. Bass, *secty.*, Geophysical Society of Tulsa, Texaco, Inc., P.O. Box 2420, Tulsa, Okla.
Robert B. Fisher, *treas.*

**Utah Geophysical Society (17)**
L. D. Oster, *pres.*
K. L. Cook, *1st v-pres.*
H. H. Nuttli, *2nd v-pres.*
D. J. O'Halloran, *secty.-treas.*, Standard Oil of California, P.O. Box 1076, Salt Lake City, Utah.

**Asociacion Venezolana de Geofisica (20),** Caracas, Venezuela, chartered January 5, 1959, officers elected in March.
E. J. Assiter, *pres.*
D. W. Danz, *1st v-pres.*
Gunther Fiedler, *2nd v-pres.*
Manuel Zegarra, *secty.*, Asociacion Venezolana de Geofisica, Phillips Petroleum Co., Apartado 1031, Caracas, Venezuela.
C. O. Hill, *treas.*

STUDENT SOCIETIES AFFILIATED

**Colorado School of Mines Society of Student Geophysicists**
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado.
*Meetings:* Monthly, 2nd Monday, 4:00 P.M.

**Geophysical Society of Saint Louis University**
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois.
*Meetings:* Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology.

**SEG Houston Student Section**
Billie Gail Dopslauf, *secty.* 2121 Hollister, Houston, Texas

**University of Toronto Geophysical Society**
B. R. Krause, *secty.* 502 Gilbert Ave., Apt. 107, Toronto, Ont., Canada

**University of Tulsa Student Geophysical Society**
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma.
*Meetings:* Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

**Trans-Pecos Student Section**
El Paso, Texas

**Pennsylvania State University Geophysical Society**
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
*Meetings:* to be announced.

**University of Utah Geophysical Society**
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah.
*Meetings:* Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced.

**A & M College of Texas Student Geophysical Society**
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas.

## SOCIETY AFFILIATIONS

### American Association for the Advancement of Science

*SEG is affiliated under Section E, Geology and Geography*
1515 Massachusetts Avenue
Washington 5, D. C.
Paul E. Klopsteg, *President*
Paul A. Scherer, *Treasurer*
Dael Wolfle, *Executive Officer*

### The American Association of Petroleum Geologists

*A Cooperative relationship*
Box 979
Tulsa 1, Oklahoma
L. G. Weeks, *President*
A. H. Bell, *Vice-President*
H. T. Morley, *Secretary-Treasurer*
G. E. Murray, *Editor*
G. S. Buchanan, *Past President*
R. H. Dott, *Executive Director*

### European Association of Exploration Geophysicists

*Mutually affiliated*
30, Carel Van Bylandtlaan
The Hague, Netherlands
J. M. Bruckshaw, *President*
V. Baranov, *Vice-President*
B. Baars, *Secretary-Treasurer*
O. Koefoed, *Editor*
L. Solaini, *Past President*

### National Research Council, Division of Earth Sciences

*SEG is a member society*
2101 Constitution Ave., N.W.
Washington 25, D. C.
John N. Adkins, *Chairman*
Harry H. Hess, *Past Chairman*
Edward B. Espenshade, Jr., *Chairman-Designate*
William R. Thurston, *Executive Secretary*

### Petroleum Exploration Society of Libya

*Mutually Affiliated*
P. O. Box 900
Tripoli, Libya
R. E. Doan, *President*
P. F. Burollet, *1st Vice-President*
J. F. Rominger, *2nd Vice-President*
J. C. Wilson, *Secretary*
P. Arni, *Treasurer*
J. S. Cullison, *Director*
R. S. M. Templeton, *Director*

## MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

### APPLICATIONS FOR ACTIVE MEMBERSHIP

Arthur D. Bennett (J. D. Eisler, N. R. Sparks, C. C. Lash, Daniel Silverman)
Kenneth A. Brown (R. A. Paulus, Frank Ittner, L. M. Scofield, B. C. Jones)
Clyde S. Deal (R. L. Long, Rodalfo Martin, J. A. Long)
Fred W. Hefer (L. B. McManis, L. W. Erath, Don Melton, S. Kaufman)
James S. Russell-Redman (W. P. Oquilvie, R. K. Moyse, H. A. Winkler, Iain Marshall)
Robert A. Wahnau (Sam L. Evans, M. E. Trostle, R. H. Wright, N. W. Mann)
George F. Weis (Erle W. Gilbert, D. J. Shriner, R. J. Yuzbick)

### APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

William Mac Ard (J. A. Standridge, E. J. Marti, C. V. Aderman, C. C. Zimmerman)
Wayne D. Boyd (Homer Roberts, O. E. Prather, Richard Martin, Lee Davis)
George S. Brownwell (J. B. Lovejoy, A. L. Barnes, Floyd Acklin, Jr., Wm. D. Boone)
Wesley Eckley (J. T. Hartman, W. J. Taylor, Jr., R. C. Hilton, P. E. Deatherage)
Bruce M. Ganek (J. W. Hoover, H. E. Stommel, R. B. Wilcoxin, H. F. Sagoci)
Francis L. Hickey (C. J. Blundum, E. T. Cook, J. Hamilton)
Glenn E. Hunter (W. T. Lea, J. M. Armstrong, E. L. Current, S. R. Lake)
John Payson Lambe (George L. Robb, T. S. Green, A. Maxwell House)
George W. Lewis (J. A. Standridge, A. F. Borello, E. S. Hastings, S. A. Spencer)
Harold M. Meadow (F. A. Van Melle, T. E. Young, L. F. Schombel, D. Vander Stoep)
James I. Mercier (Barry Koch, W. D. Cortright, E. A. Kiesler, Roberty Dyke)
Thomas J. Miller (C. C. Zimmerman, H. W. McDonald, A. Klaveners, S. Weatherby)
John Petrocco (R. E. Faudry, C. C. Sellers, C. B. Smith, H. C. Talley)
Jack William Poe (K. A. Robertson, Robert Mills, E. G. Schempf, S. O. Patterson)
Joe Louis Poindexter (Louis Poindexter, J. A. Trybig, J. R. Ording, V. D. Clark)
James K. Riley Jr. (T. I. Harkins, C. P. Harkins, N. N. Zirbel)
Richard J. Runge (N. A. Riley, F. G. Blake, A. E. Tilley, L. P. Stephenson)
F. Augustus Seamans (O. B. Hocker, W. H. Gibson, Alton McClung, J. P. House)
James Wm. Schneider (C. B. Smith, S. B. Stewart, C. C. Sellers)
John A. Steacy (Albert P. Crosby, H. M. Rackets, Thomas Portwood, Jr., J. A. Long)
Lester H. Stephens (A. P. Wendler, Glen Bader, S. R. Allen)
Pieter Tackenberg (O. B. Manes, V. J. Hunzicker, H. M. Rackets, T. B. Portwood)
Thomas R. B. Webb (E. B. Manchee, R. B. Oldaker, F. A. Hale, G. C. Alvey)
John M. Willey (K. H. Waters, A. J. Oden, B. J. Sorells, J. H. Frasher)
Enrique H. Yramatequi (E. B. Kasiske, R. G. Avenius, J. C. Peffer, P. P. Conrad)

# ANNOUNCEMENTS

## ERRATA FOR "LESSONS IN SEISMIC COMPUTING"

Reprints of the Errata for "Lessons in Seismic Computing" are available upon request from the Business Office, Box 1536, Tulsa 1, Oklahoma.

## TEXAS INSTRUMENTS CO-FOUNDER AND WIFE GIVE $1,250,000 TO M.I.T. TO ESTABLISH EARTH SCIENCES SCHOLARSHIPS FOR SOUTHWEST STUDENTS

A gift exceeding $1,250,000 by Mr. and Mrs. Eugene McDermott of Dallas, Texas, to the Massachusetts Institute of Technology for scholarships, was announced by Dr. Julius A. Stratton, President.

The amount represents the market value of 6,000 shares of stock in Texas Instruments Incorporated, which constituted the gift. It is the largest gift for scholarships ever received by M.I.T.

The scholarships will be awarded to students from Texas or other states of the Southwest, with preference given to those studying the earth sciences—geology, geophysics, meteorology, and oceanography—or allied fields.

Dr. Stratton pointed out that it is especially appropriate that the McDermott Scholarships will give preference to earth sciences students since a new Earth Sciences building is to be built with funds given to the Institute by Mr. McDermott's associate, Cecil H. Green, and Mrs. Green. Mr. Green, an alumnus of M.I.T. and a Member of the Corporation, was a co-founder and is a Director of Texas Instruments.

Mr. McDermott is Chairman of the Executive Committee of Texas Instruments. Following graduation from Stevens Institute of Technology and a period during which he worked for Goodyear Rubber Company and Western Electric and received his Master of Arts degree in Physics at Columbia University, Mr. McDermott entered the oil exploration field in 1925, when he participated in the founding of Geophysical Research Corporation. Subsequently, in 1930, he co-founded Geophysical Service Inc., the company from which Texas Instruments evolved.

Born in Brooklyn, New York, Mr. McDermott has resided in Texas for more than 30 years. His and his wife's interest in education is evidenced by a number of associations. Mr. McDermott served as President of St. Mark's School for Boys in Dallas from 1945 to 1955 and he continues as a member of its Board of Trustees. He is a co-founder and Trustee of the Graduate Research Center of Dallas, a member of the Executive Committee of the Board of Trustees of the Texas Research Foundation, a member of the Boards of Trustees of The Hockaday School and the Southwestern Medical Foundation, a member of the Visiting Committee of the Physics Department of M.I.T. and a member of the boards of numerous other civic and cultural institutions, such as the Dallas Art Museum, and the Dallas Theater Center. He is a past President of the Society of Exploration Geophysicists and is a member of a number of leading scientific societies.

## TENTH ANNUAL STUDENT COOPERATIVE PLAN

Fifty-eight top-level earth scientists gathered in Dallas June 14–18 to take part in the orientation session which preceded the tenth annual Student Cooperative Plan, sponsored by Geophysical Service Inc., a Texas Instruments company.

The group included representatives from seven major oil companies and nine universities and scientific research organizations.

The GSI Student Cooperative Plan is a program begun in 1951 by GSI Honorary Board Chairman Cecil H. Green and Dr. Robert R. Shrock, head of the Department of Geology and Geophysics at the Massachusetts Institute of Technology.

Mr. Green said the plan was designed to give interested and qualified students, who are considering petroleum exploration as a career, a chance to actually participate in all phases of exploration geophysics.

HONOR STUDENT RECEIVES CECIL GREEN GOLD MEDAL

JAMES R. HEAVENER (right), a native of Charleston, W. Va., was awarded the Cecil Green Gold Medal during the 86th Annual Commencement ceremonies at the Colorado School of Mines. Mr. Heavener is shown here with DR. GREEN, who holds an honorary doctorate from the mineral engineering college. Mr. Heavener, who was graduated with high honors (3.6 academic average out of a possible 4.0), received a professional geophysical engineering degree. He began working for Geophysical Service, Inc., in June.

Eighteen students representing sixteen universities participated this year. In all, 197 students from 53 colleges have taken part in the program.

This year, in addition to talks given by oil company exploration, production and research personnel, several sessions were devoted to oceanography, geochemistry, a discussion of the Mohole site location, meteorology and the role of the geosciences in solving problems associated with technology of the space age.

Oil company and university faculty participants this year were:

O. C. Clifford, Jr., and John P. Woods, Atlantic Refining Company; Sir Edward C. Bullard, Cambridge University; John W. Vanderwilt, Colorado School of Mines; R. W. Anderson, M. M. Backus, J. W. Brown, K. E. Burg, R. C. Dunlap, Jr., R. D. Everett, R. A. Geyer, Freeman Gilbert, R. J. Graebner, Cecil H. Green, B. A. Harris, Stanley Laster, N. W. Mann, C. M. Moore, Jr., P. M. Ralph, and M. K. Smith, Geophysical Service, Inc.

Charles C. Mason, Humble Oil & Refining Company; Jack Oliver, Lamont Geological Observatory; Robert M. Fano, Henry G. Houghton, Yuk-Wing Lee, Robert R. Shrock, and John W. Win-

chester, Massachusetts Institute of Technology; Walter H. Munk, Scripps Institution of Oceanography; F. A. Van Melle, Shell Development Company; Paul L. Lyons, Sinclair Oil & Gas Company; C. Ivan Alexander, C. D. McClure, Frank J. McDonal, Paul P. Reichertz, R. L. Sengbush, Nelson P. Stevens, Allen A. Stripling, George C. Wallick, and William C. Woolley, Socony Mobile Oil Company.

Jack C. Kern, Standard Oil Company of Texas; D. J. Bratton, Gerhard Herzog, and D. T. McCreary, Texaco, Inc.; Paul Weaver, Texas A & M; Willis Adcock, F. J. Agnich, F. A. Brock, Fred Bucy, Robert Foote, S. T. Harris, E. R. Kinsley, Chester W. Nimitz, Jr., George Sarrafian, Mark Sheperd, and Lawrence Strickland, Texas Instruments Incorporated; R. E. Jackson, Texas Women's University; Athelstan Spilhaus, University of Minnesota; Columbus O'D. Iselin, and J. Brackett Hersey, Woods Hole Oceanographic Institution.

## THREE NEW AIME LOCAL SECTIONS ORGANIZED

The 36,000-member American Institute of Mining, Metallurgical, and Petroleum Engineers has announced the organization of three new Local Sections. These are the Carolinas Section, embracing both North Carolina and South Carolina, heretofore in the Southeast Section; Wisconsin Section, taking in 30 Wisconsin counties previously within the Chicago Section, and the Netherlands Section.

The Institute now has 94 Local Sections in the United States and other countries.

## GEORGE BOYD WEBSTER CHAIR OF MINING ENGINEERING ESTABLISHED AT McGILL UNIVERSITY

Establishment of the George Boyd Webster Chair of Mining Engineering at McGill University through the donation of $350,000 by G. B. Webster, Toronto mining engineer and financier, was announced by Dr. F. Cyril James, principal and vice-chancellor on behalf of the Board of Governors.

This donation by a McGill graduate will make possible, in this case, the return to Canada from the United States of an engineer and scientist with worldwide experience in geophysical methods of exploration.

The first incumbent of the new chair will be DR. L. P. GELDART of Palo Alto, California, a Canadian who received his early education at Mount Allison University.

Dr. Geldart entered McGill for post-graduate training under Dr. J. Stuart Foster, gaining a Ph.D. in physics in 1940. He then studied meteorology at the University of Toronto. From 1942 to 1947 he was head of the physics department at Acadia University. From there he went to the California Institute of Technology, where he obtained a professional engineering degree in geophysics. He spent 11½ years with Standard Oil of California and later went with the California Exploration Company, in which he now has the status of chief geophysicist of the foreign department.

The appointment of a man of such diversified training and experience will make possible, it was pointed out at McGill, an intensification and unification of the work of applied geophysics within the faculty of engineering.

McGill pioneered in the application of geology and physics in the exploration of deep underlying ore bodies through the early work of the late Dean A. S. Eve, the late Dr. Horace Watson, and Dr. David A. Keys.

This work is now being carried on jointly by the department of physics and geology. Application of knowledge in this field calls for a variety of disciplines, including not only geology and physics, but also mining, civil and mechanical engineering.

Under the auspices of the new chair, it will be possible to extend the university's scientific work and teaching in an area which has become of increasing importance to Canada through the widespread search for oil and mineral deposits, and their economic extraction and processing.

The donor of the chair, which bears his name, was born in Brockville, Ont., and educated at the Brockville and Ottawa Collegiates before entering McGill where he graduated in mining engineering in 1904.

### Associate Editor Appointed

Mr. Turner L. Kunkel of Texaco, Inc., in Houston has been appointed to the editorial staff of Geophysics as the Associate Editor for Exploration Seismology.

## PROPOSED AMENDMENTS TO THE CONSTITUTION AND BYLAWS

In accordance with Article XVIII of the SEG Constitution, the following amendments have been proposed by Frank Searcy, First Vice-President. Delete words in (parentheses) and add words in *italics*.

### Constitution, Article VIII. Council

Section 3. A (joint) meeting of the (outgoing and incoming) Council(s) shall be held at the call and under the chairmanship of the (outgoing) *incoming* president (during) *immediately following* the annual meeting of the society. At this (joint) meeting the Council(s) shall (hear) *receive* reports from all officers and committees and review the activities of the society for the past year. (With the advice of the outgoing Council,) The (incoming) Council (under the chairmanship of the incoming President) shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairman *and outgoing officers* shall attend this meeting *with the privilege to speak but not to vote.* (but, as chairmen, shall have no vote.)

In accordance with Article XVII of the Constitution, the following amendment to the Bylaws has been proposed by Nelson Steenland, Editor.

### Bylaws, Article I. Publications

Delete Section 3 and renumber Sections 4, 5, and 6, respectively as 3, 4 and 5.

## PERSONAL ITEMS

FRED A. BROCK and DONALD P. VENKER have been named Manager and Customer Requirements Manager, respectively, of the Geophysical products branch of the Texas Instruments Incorporated Instrumentation product group at Houston.

The appointments were announced by J. Fred Bucy, Manager of the Petroleum instrumentation department of TI's Geosciences & Instrumentation division.

Both men formerly were with TI's oil exploration subsidiary, Geophysical Service Inc., and both in recent years have been engaged in the design and development of seismic instrumentation.

Brock was chief research engineer for GSI prior to his new assignment. He has a Bachelor of Science degree in electrical engineering from Southern Methodist University and did post-graduate work at Harvard and Massachusetts Institute of Technology.

Venker has a Bachelor of Science degree in geophysical engineering from St. Louis University, where he returned for post-graduate studies after several years as a computer and party chief with GSI. He has been with TI in Houston since 1957.

DR. C. H. G. OLDHAM has transferred to the La Habra Laboratory and has been appointed Senior Research Geophysicist in the Geophysics Research Section.

Dr. Oldham studied at the University of Reading, England, and the University of Toronto. He joined the staff of the La Habra Laboratory in 1954, transferring in 1957 to the California Exploration Company where he was appointed Senior Gravity and Magnetic Analyst.

S. H. YUNGUL has been appointed to the position of Senior Research Geophysicist in the Geophysics Research Section, La Habra Laboratory.

Mr. Yungul attended universities in Turkey, France and the United States. He accumulated a wide background of field experience as Chief Geophysicist for an agency of the Turkish Government before joining Cal Research in 1955.

JOHN M. CRAWFORD has been promoted to a newly created position of Assistant Manager—Research and Development Department, Continental Oil Company. Mr. Crawford will be responsible for the activities of the Production, Exploration, and Central Research divisions. W. E. N. DOTY has been promoted to Director, Exploration Research Division, replacing Mr. Crawford.

C. M. FERREE, Assistant Regional Geophysicist, Continental Oil Co., Denver, was promoted to Headquarters Geophysicist—Operations Division, Geophysical Section, with headquarters in Ponca City, Oklahoma.

GRAHAM W. FENNER, Division Geophysicist, Ardmore Division of the Central Region, Continental Oil Co., was promoted to the position of Assistant Regional Geophysicist, Rocky Mountain Region. He replaced Mr. Ferree.

DANIEL H. SULLIVAN, Geophysical Supervisor, Wichita Falls Division, Southwestern Region, Continental Oil Co., was promoted to Division Geophysicist, Ardmore Division, Central Region, replacing Mr. Fenner.

G. H. SWENUMSON who had been acting as Regional Geophysicist, Continental Oil Co., for the past year in the Southwestern Region, Fort Worth, was transferred to the position of Assistant to the Manager, Geophysical Section, Houston.

GSI President R. C. DUNLAP, JR., said WILLIAM EDWARD DICKSON has been named to the post of supervisor in Madrid, where he will be responsible for the operations of GSI exploration field parties in the Spanish Sahara. Mr. Dickson was formerly in GSI's London, England office. He has been with GSI since 1931. Prior to his London assignment, he was seismic operations supervisor in Canada.

LEWIS SOLE, a twenty-five year veteran with GSI, will join the personnel department in Dallas as administrator for GSI field parties in the Eastern Hemisphere and Latin America. Sole joined GSI in 1933 and has been a seismic party chief since 1950.

Continental Oil Company's Geophysical Department announces that:

W. E. RICHARDSON, Development Geophysicist in the Equipment Division, has been transferred to the Oasis Oil Company of Libya; P. O. Boxes 317, 377, 561, Tripoli, Libya.

H. H. MOODY, Superintendent of the Equipment Division, resigned June 30th to live in Pompano Beach, Florida. His address will be Box 2843, Hamilton Station.

E. F. BIRDSALL, formerly Assistant to the Manager in Houston, is now Staff Geophysicist, Foreign Department, and located at the following address: c/o S.A.P., Boite Postale 203, Dakar, Senegal, French West Africa.

SEGUNDO G. ARGUDO is now at Colorado School of Mines, Golden, Colorado, pursuing an advanced degree in Geophysics. He was formerly with Standard Oil Company of California, with assignment in Havana, Cuba. His new address: 1614 Iris Street, Denver 15, Colorado.

LUCIUS C. GEER, formerly the geophysicist for Union's Southwest Louisiana District in Lafayette, Louisiana, has been transferred to the Corpus Christi Area office as Assistant District Geologist in charge.

CALVIN SPIVEY, with Petty Geophysical Company, has been transferred to Australia as area manager.

H. B. SMITHWICK, formerly with The Atlantic Refining Company is now an independent consulting geophysicist. His new address is 2352 Coronet Place, Jackson 4, Mississippi.

S. GORENBEIN, formerly with California Research Corporation, is now a member of the technical staff of Hughes Aircraft Company, Fullerton, California.

M. DAVID ROSTOKER completed his Ph.D. in Geology at Boston University and has accepted a position as head of the Science Department at Quincy Junior College, Quincy, Massachusetts.

C. K. SHEPHERD, New York, manager of acquisitions in the foreign department of Continental Oil Co., was named to succeed Hal F. Nabors, as general manager of the Central division at Oklahoma City. Nabors recently was named manager of production in the foreign department at New York.

Shepherd joined the company in 1937 on a geophysical crew; in 1955 was named exploration manager for Sahara Petroleum Co. in Egypt, and became president of that firm in 1957. He has been at the New York post since 1958.

RICHARD A. SNOW has been promoted to Manager of the Geophysical Instrument Product Group of Varian Associates, sustaining member of the SEG. E. L. WATSON, Manager of Instrument Field Engineering, Instrument Division, has become company representative to SEG for Varian. Both are in the headquarters' offices of the company at 611 Hansen Way, Palo Alto, California.

R. A. BLACK has resigned his appointment as Associate Professor at the Missouri School of Mines and Metallurgy to accept a position as geophysicist with the U. S. Geological Survey.

The Board of Directors of The Geotechnical Corporation, Garland, Texas, recently announced the election DR. WILLIAM B. HEROY, JR. to the office of Executive Vice-President. Dr. Heroy joined Geotech in 1945 and was subsequently appointed a Vice-President and member of the Board of Directors.

In his new position, Dr. Heroy will direct and coordinate the operations of the company.

## CALENDAR OF MEETINGS

1960

October

12–14 Third Annual Meeting, Southwestern Federation of Geological Societies, Abilene, Texas.
19–21 Gulf Coast Association of Geological Societies, Biloxi, Mississippi.
31–Nov. 2 GSA Annual Meeting, Denver, Colorado.

November

3–4 Pacific Section AAPG, Los Angeles.
7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston, Texas.
14–16 API, Chicago, Illinois.

1961

February

19–23 AIME Annual Meeting, St. Louis, Missouri.

March

20–23 IRE National Convention, New York City.

April

9–11 Society of Exploration Geophysicists, 14th Annual Midwestern Meeting, Skirvin Hotel, Oklahoma City, Oklahoma.
24–27 AAPG-SEPM Annual Meeting, Denver, Colorado.

October

8–11 Society of Petroleum Engineers of A.I.M.E., Annual Meeting, Dallas, Texas.
18–21 AAPG Mid-Continent Regional Meeting, Amarillo, Texas.
25–27 Gulf Coast Association of Geological Societies, San Antonio, Texas.

November

2–4 GSA Annual Meeting, Cincinnati, Ohio.
5–9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver, Colorado.
9–10 Pacific Section AAPG, Los Angeles.
13–15 API, Chicago, Illinois.

1962

March

26–29 AAPG-SEPM Annual Meeting, San Francisco, California.
26–29 IRE National Convention, New York City.

September

7–10 Society of Petroleum Engineers of A.I.M.E. Annual Meeting, Los Angeles, California.
17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta.

Oct. 31–Nov. 3 Gulf Coast Ass'n Geological Societies, New Orleans, La.

November

12–14 GDA Annual Meeting, Houston, Texas.

1963

March

25–28 AAPG-SEPM Annual Meeting, Houston, Texas.

October

6–9 Society of Petroleum Engineers of A.I.M.E. Annual Meeting, New Orleans, La.
24–28 Society of Exploration Geophysicists, 33rd Annual International Meeting, New Orleans, La.

November

13–16 Gulf Coast Ass'n of Geological Societies, Hot Springs, Ark.

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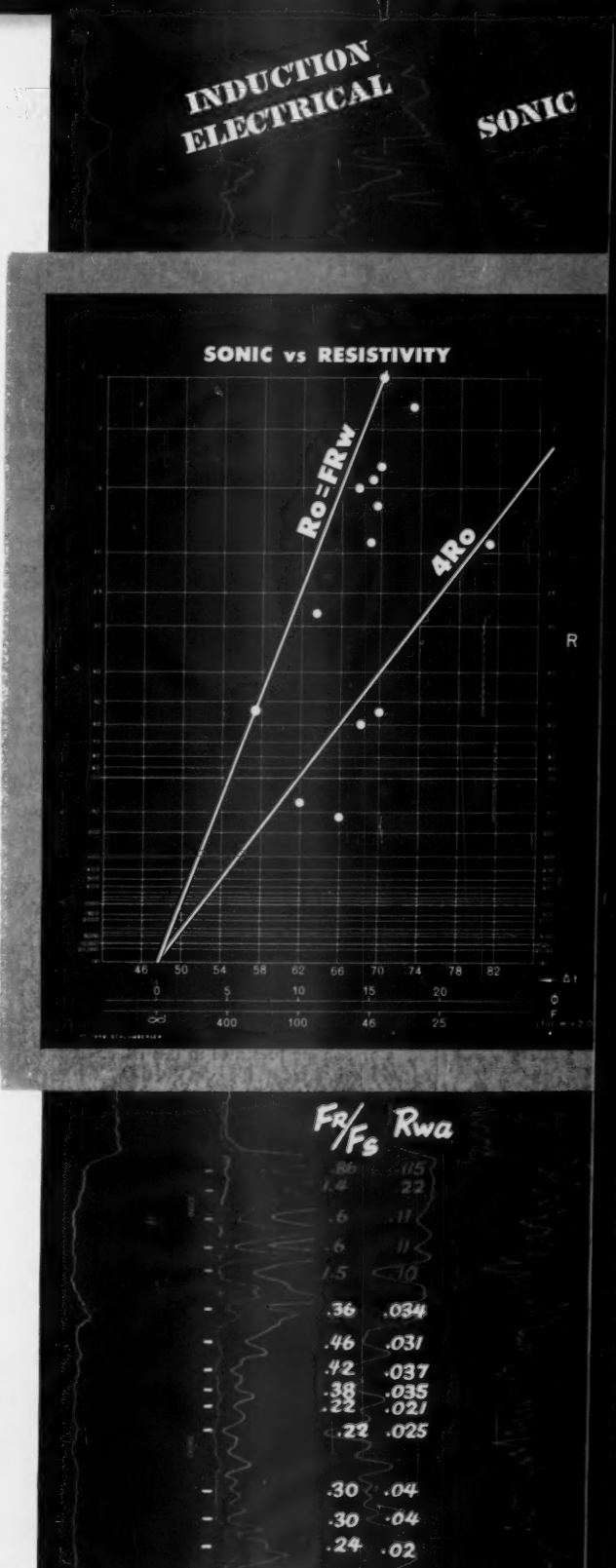

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Three-Dimensional Seismic Exploration on a Mass-Scale in the Carpathians by V. D. Zav'yalov

Standard Equipment for Radioactive Logging by D. F. Bespalov and B. G. Erozolimsky

This issue also contains a nearly complete listing of titles and abstracts of technical papers presented before twenty-three local sections of SEG during the 1958-59 season.

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This issue contains four papers relating to the interpretation of seismic and gravity data. A fifth paper discusses seismic exploration in the Appalachian Region.

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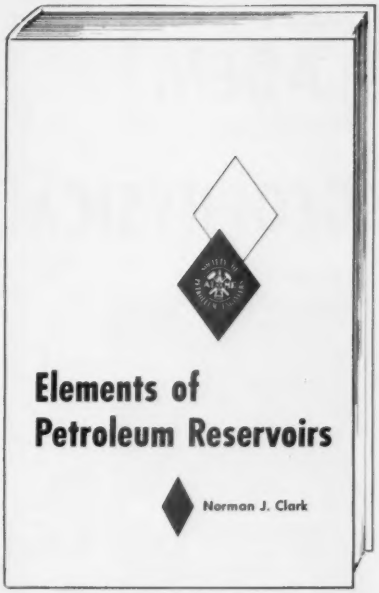


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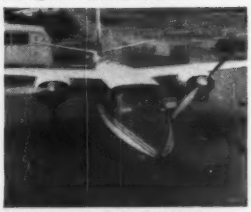

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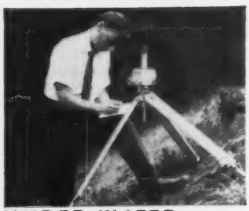

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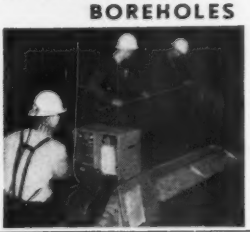

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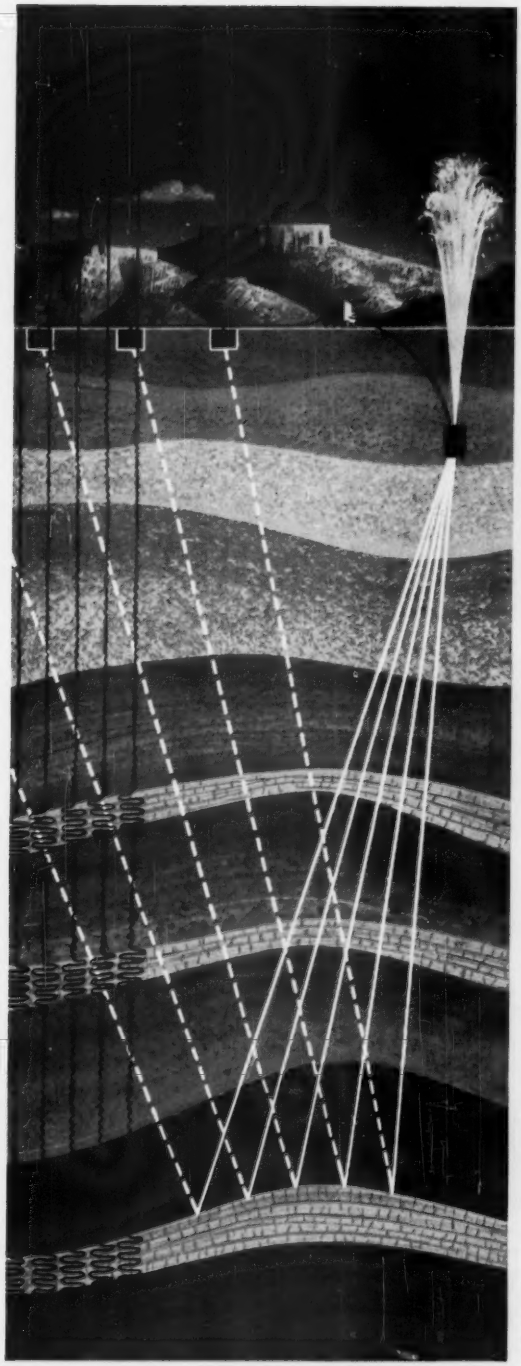

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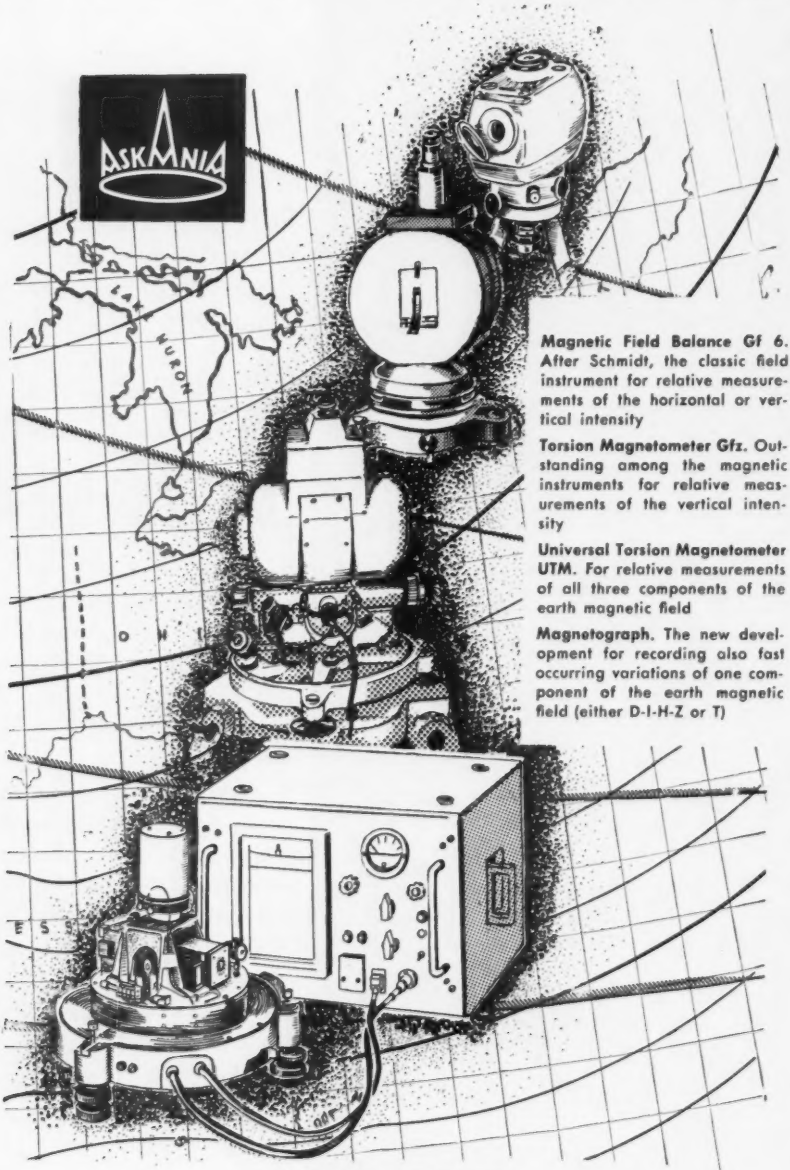


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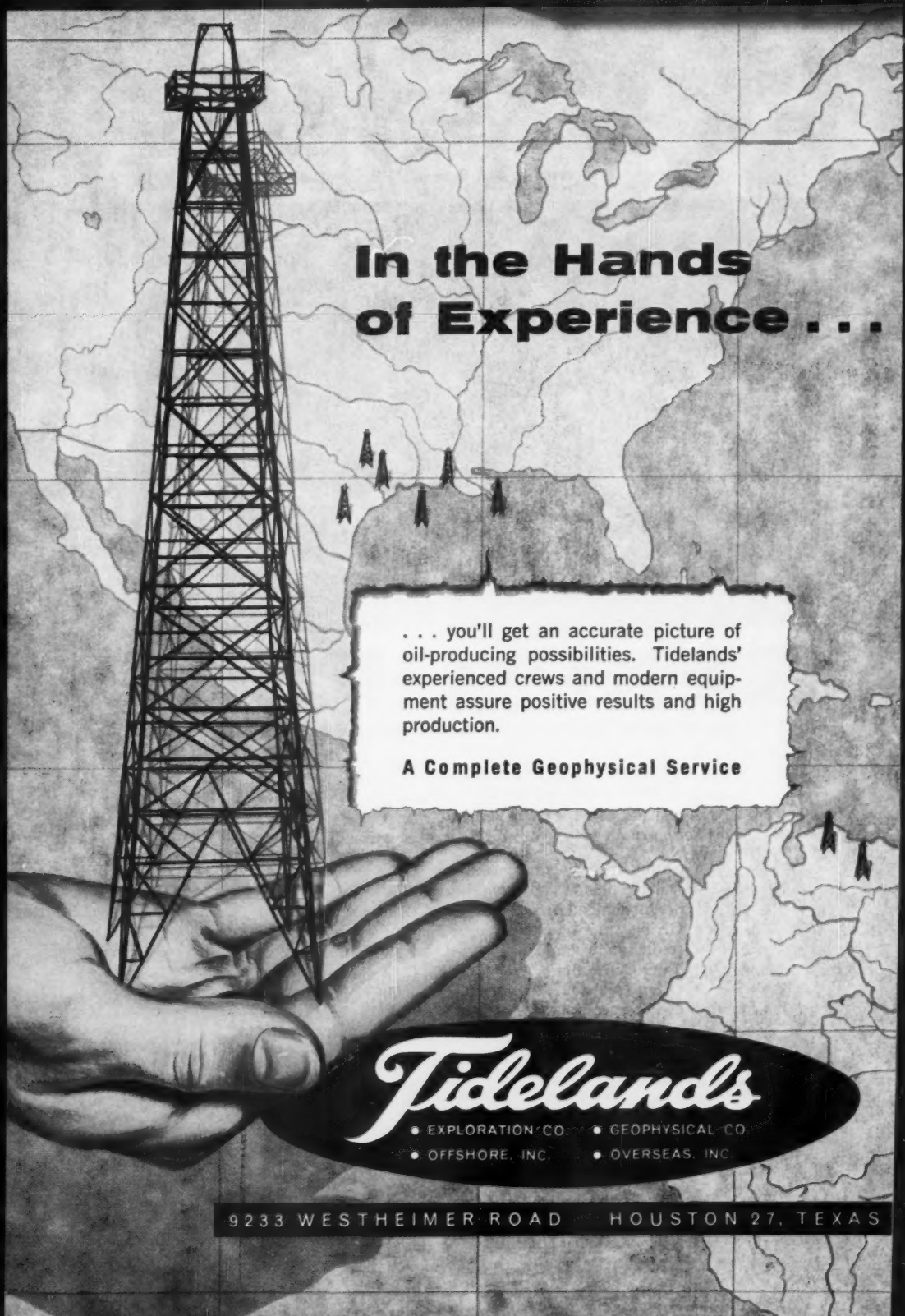
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Kodak

They are not going to tell him how to fuze a nuclear warhead.

He is not going to tell them why Kodak's direct-writing paper responds so well to Permanizing treatment.

Hugh L. Odell (left), supervisor of instrument services at Sandia Corporation's Livermore (Calif.) Laboratory, introduces Sandia's Wilford Vandermolen to Kodak's John Pardee (center). Mr. Vandermolen's function is to record on photographic paper signals such as those indicating the condition of the fuzing mechanism inside the casing of a nuclear bomb under various applied forces. Mr. Pardee's function is to co-ordinate development of new combinations of sensitized paper, chemicals, and processing techniques with the changing needs of users of Kodak Linagraph Papers.

Some people's secrets are bigger than other people's secrets. Some of the biggest are kept by Sandia Corporation, whose responsibilities include the ordnance engineering of nuclear weapons. Everything had better be up to date at Sandia.

On this visit John Pardee found out that the up-to-date view on **Kodak Linagraph Direct Print Paper** is a little different from what we had in mind. We developed the product for instant results and only occasional need of preservation treatment with **Kodak Linagraph Permanizing Developer.** Turns out that at Sandia's Livermore Laboratory they do the preservation treatment routinely on many recordings (because photocopies are needed), but they need the no-processing, instant-see feature for quick-look appraisal of information recorded on magnetic tape.

For a booklet on these two companion products write

*Photorecording Methods Division*

**EASTMAN KODAK COMPANY,** Rochester 4, N.Y.

*(Continued from page 4)*

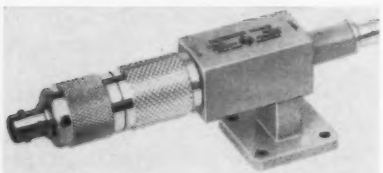
## INSTRUMENTATION DEVELOPMENT

Empire Geophysical, Inc. has announced an instrumentation development at its Midland Tape Reduction Center that offers new versatility in the processing of magnetic tapes for seismic application.

According to Empire President, Howard Itten, Empire is now able to provide service for complete data reductions from SIE, SIE configuration type tapes, Techno, Techno configuration type tapes, magnedisc and EIC tapes. The services include all types of reduction processes from field tapes as well as the transcribing or transferring from one type of tape to another. The system includes both AM and FM facilities, with all combinations of the two systems available to the customer. Transcribing is performed on a simultaneous 24-trace operation. Reduction from field tapes to the various modes of presentation and for dynamic and static corrections is performed in the highly versatile Seismac sequential system, as well as the alternate SIE MS-12 sequential correction system. Multiple drums provide great flexibility for horizontal stacking, as well as the process of compositing. The system is readily adapted to sequential field recording, such as is encountered in weight dropping operations, as well as for all conventional seismic techniques.

The installation at Midland has provided Empire with the most complete and largest system of its kind for magnetic tape processing in the United States. **Empire Geophysical, Inc., 6000 Camp Bowie Blvd., Fort Worth, Texas.**

## HARMONIC MIXERS



Two new harmonic mixers which speed and simplify frequency measurements up to 18 KMC are now available from Hewlett-Packard Company.

Model P932A fixed tuned harmonic mixer, operating in the 12.4 to 18 KMC P-Band, mounts directly in a waveguide system and operates with a Hewlett-Packard Model 540A or 540B transfer oscillator. The oscillator output is applied directly to the mixer, which generates harmonics and mixes them with an applied unknown waveguide frequency. The mixer's beat frequency output is applied to the 540's oscilloscope, the oscillator tuned for zero beat scope indication, and the oscillator frequency setting noted.

Simple multiplication of the 540 dial frequency by the harmonic number yields the unknown frequency to within 0.5%. Measuring the oscillator frequency on a Hewlett-Packard 524 series counter increases the accuracy of measurement on clean cw signals up to 1 part in $10^7$.

Model P932A's maximum input power is 100 mw, and its minimum video output is 0.1 mv rms with 0 dbm input.

The other harmonic mixer, Model 934A, operates from 1 to 12.4 KMC, and extends the range of the Hewlett-Packard 540A transfer oscillator from 5 KMC to 12.4 KMC. The 934A offers the same advantages as the P932A, including the fixed tuned feature eliminating tedious adjustment. Its maximum input power is 100 mw, and its typical sensitivity is −45 dbm at the mid-range points.

The Model P932A is priced at $250 and is currently available for delivery from stock. The Model 934A is priced at $150 and is currently available for delivery from stock. **Hewlett-Packard Company, 1501 Page Mill Road, Palo Alto, California.**

## OSCILLOGRAPH RECORDING FILM EKTACHROME ER SYSTEM

A new oscillograph recording film and a high-speed color motion picture system for instrumentation were announced by Eastman Kodak Company before the Society of Photographic Instrumentation Engineers Technical Symposium.

The new oscillograph material, Linagraph Recording Film, Estar Base, combines emulsion characteristics which produce sharp, black, easily-read traces with the exceptional dimensional stability of Kodak's recently-announced polyethylene terephthalate Estar base.

The film is highly sensitive to the blue region of the spectrum, yields high contrast for discernment of fine traces, and is fog free to further aid legibility of the traces. An orange anti-halation backing, which enhances image sharpness, instantly disappears upon immersion in the developer.

*(Continued on page 38)*

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Century Geophysical Corporation, with its 44 geophysical units presently spread across the globe, is backed and strengthened by the research and development laboratories and the manufacturing facilities of Century Electronics & Instruments, Inc. These two affiliates are working partners in providing many industries with technical services and electronic instrumentation and equipment.

Seismic and gravity meter crew operations, review geophysical interpretations, velocity surveys, data center processing, uranium exploration logging and radiometric analysis are some of the general areas where Century has gained a large backlog of experience and wide acceptance.

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Field party on survey for proposed Canyon Dam on Texas' Guadalupe River.

TYPE FA-176

## W&T SURVEYING ALTIMETERS SPEED HYDROLOGIC STUDY OF RESERVOIR BASIN

A ground-water and geologic survey, involving water table isograms for 400 square miles adjoining the proposed Canyon Dam Reservoir on Texas' Guadalupe River, recently was completed in 35 days. Despite difficult terrain and maximum relief of 1000 feet, over three hundred spot elevations were taken during this period. The speed with which this work was done is attributed to the use of the two-base method of altimetry employing three Wallace & Tiernan Type FA-176 Surveying Altimeters.

Technical data on the FA-176 Altimeter include: **Range** — any interval of 2000′ up to max. limit of 5000′; **Accuracy** — 2.0′; **Sensitivity** — 0.5′; **Scale Length** — 20″; **Dial Size** — 8½″ dia.

*For details on FA-176, send for Bulletin No. A-117.42*

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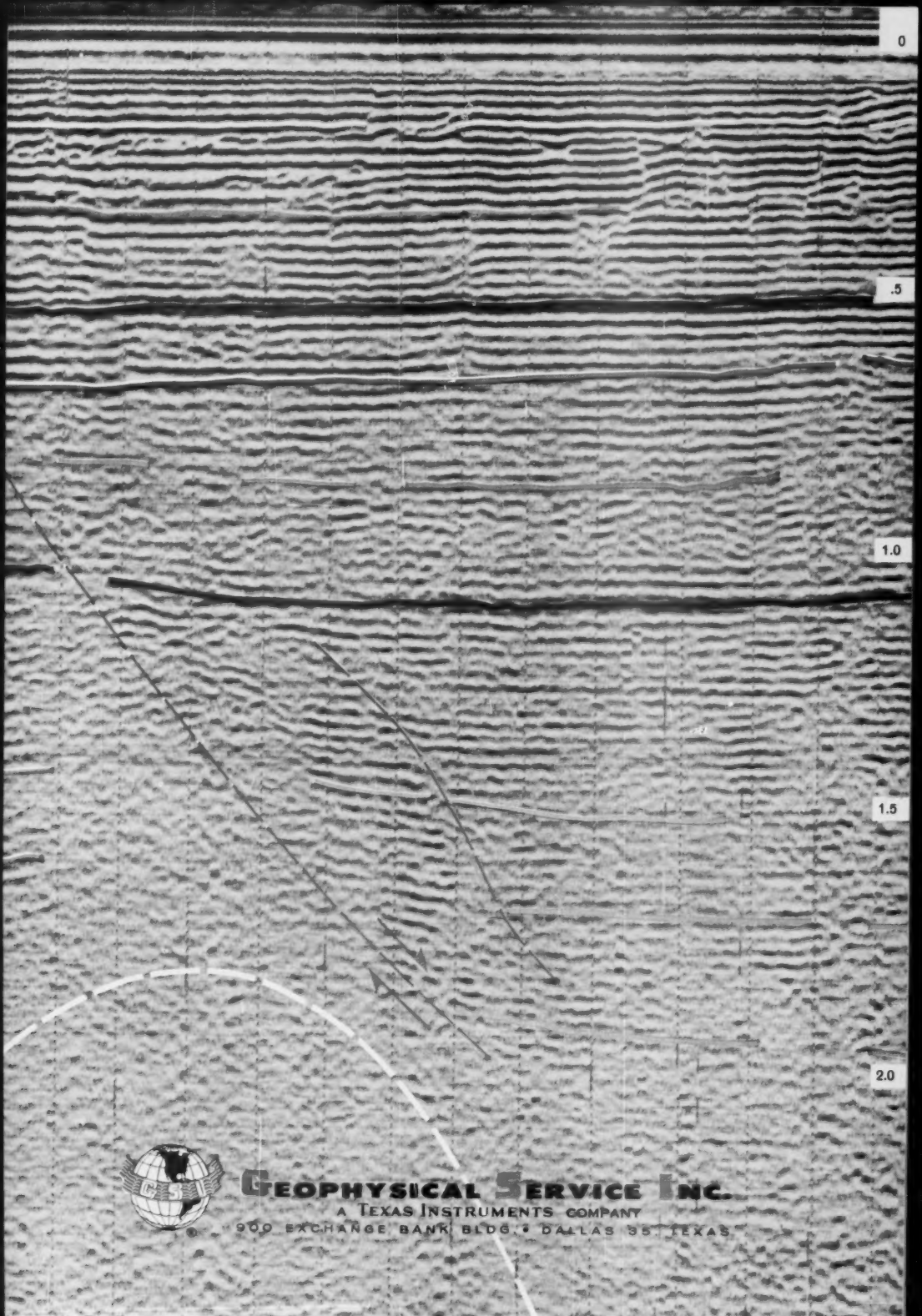


GEOPHYSICAL SERVICE INC.
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*(Continued from page 32)*

The new thin, hard emulsion permits safe, rapid, high-temperature processing. The film dries within seconds after removal from the wash.

Linagraph Recording Film, Estar Base, is available through Kodak Photo-Recording dealers in all standard widths from 2 to 52 inches, in any lengths required, and in many spooling specifications.

The Ektachrome ER System of Color Photography for Instrumentation includes the recently-introduced Ektachrome ER Film, Daylight Type, with an exposure index rating of 160, Ektachrome ER Film, Type B, rated at 125, and a new Ektachrome ER Print Film which produces high-quality duplicates of original footage.

A key advantage of the new print film is that it can be processed "head to tail" in the same machine using the same solutions and under the same time, temperature, and chemistry as the original. By using one processing machine and one set of solutions for both originals and duplicates, substantial savings are realized in space, plumbing, and equipment requirements.

Since the introduction of Ektachrome ER Daylight and Type B films, users with special requirements have obtained excellent results with the use of very high exposure indices with forced processing. Many customers report that these films have minimum grain, high acutance, and faithfulness to color over an extreme range of exposures and processing.

While both these films are suitable for screening, the new Ektachrome ER Print Film is specially designed to meet screen-viewing needs with optimum sharpness, color reproduction, and contrast.

Further information on Linagraph Recording Film, Estar Base, and the Ektachrome ER System is available from the **Photo-Recording Methods Sales Division, Eastman Kodak Company, Rochester 4, New York.**

## WWVT RECEIVER

Model WWVT is a portable, transistorized WWV receiver. The compact, lightweight unit has applications in calibrating field research gear, remote location work, and geophysical, communications, and general electronics uses.

Battery operated, it's designed for remote operations in extreme environments. A rugged, sealed metal case and potted components protect it.

Measures 9″ × 12″ × 5″; weighs 6 lbs. For additional information, write James Sherman, Sales Mgr., **Specific Products, 21051 Costanso St., Woodland Hills, Calif., or telephone DI 0-3131.**

## HELICOPTER

A new 4-place business and utility helicopter, sister ship of the Hiller 12 E, widely used in petroleum work and in exploration for oil and minerals, will go on the commercial market this fall, according to an announcement made by the Hiller Aircraft Corp. here today.

Designated the Hiller E 4, the 4-place helicopter is powered by a 320 hp Lycoming engine, a more powerful version of the same engine that lifted a 12 E copter to a world record rescue at 18,000 feet on Mt. McKinley, Alaska earlier this summer.

With more usable power than any 4-place copter, the E 4 is the only 4-place business version in the U. S. with the performance to climb vertically when fully loaded. The E 4's verified climb rate is 820 feet per minute.

*(Continued on page 50)*

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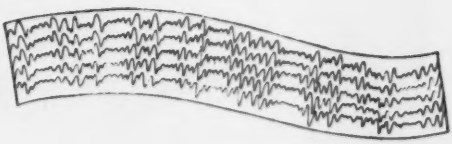

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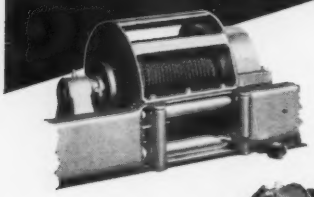

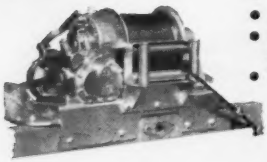

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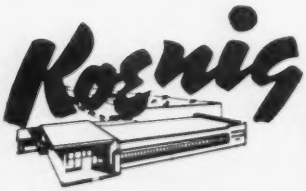


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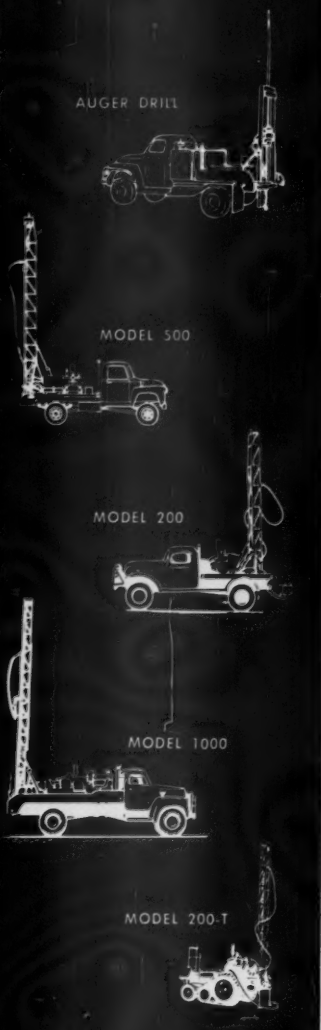


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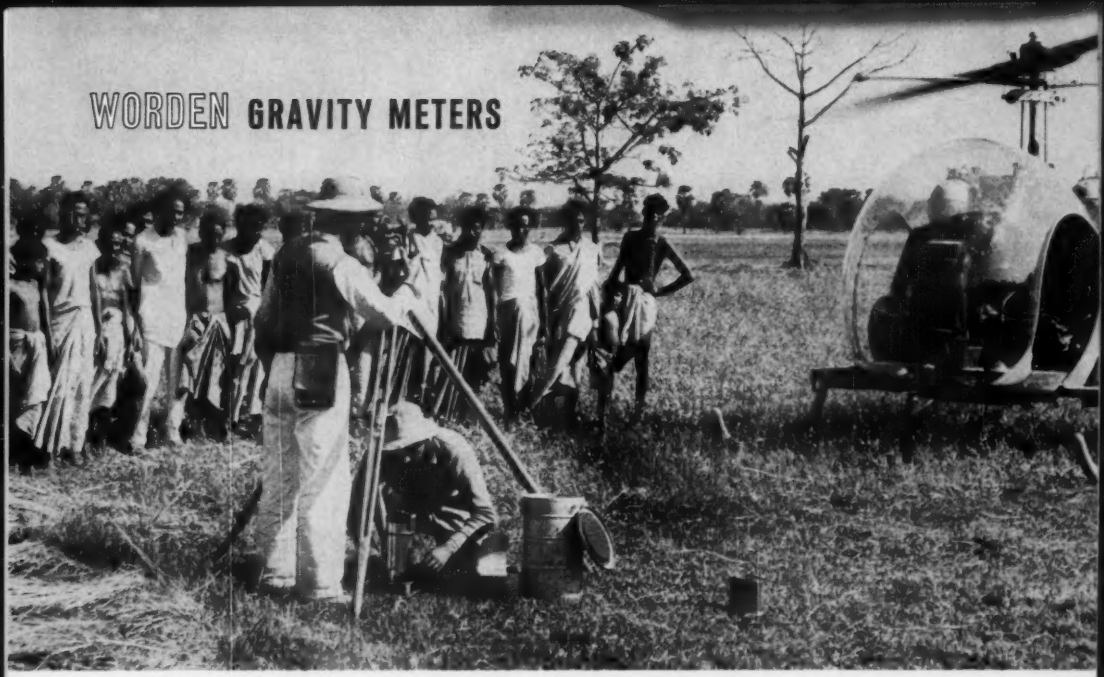


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The PIONEER is ideally suited for gravity programs in areas of limited latitude and temperature variations and where the need for less frequent base ties exists. Also available in Geodetic model.

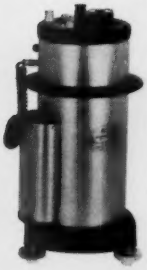
The EDUCATOR gravity meter is intended to meet the needs of educational or training programs where the required tolerances are much wider than for commercial programs.

**Specifications for the respective *WORDEN* Gravity Meters are shown at right . . . contact TI's Gravity Department for additional information.**

Springs, Wyoming

*Trademark

**Select Your *Worden* Gravity Meter from the widest combination of models and ranges in the industry!**



| When requesting a quotation, copy the specification categories in this column and specify the values desired from those found under the respective meters. | the *Master* | the *Prospector* | the *Pioneer* | the *Educator* |
|---|---|---|---|---|
| Minimum Recommended Operating Range—Specify to nearest 100 mgls.* plus latitude and elevation indication | 3000 mgls. | 3000 mgls. | 2400 mgls. | Limited . . . Will be at least 1600 mgls. |
| Minimum Total Operating Range (Reset) —Specify to nearest 100 mgls.* | 5200 mgls. | 5200 mgls. | 4000 mgls. | Limited . . . Will be at least 2000 mgls. |
| Small Dial Range | 800 Dial Divisions x Small Dial Constant (2200 on Special Order) | 800 Dial Divisions x Small Dial Constant (2200 on Special Order) | 800 Dial Divisions x Small Dial Constant | 800 Dial Divisions x Small Dial Constant |
| Small Dial Constant—Specify constant desired* | Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available) | Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available) | Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available) | 0.10-1.00 mgl./ Dial Division |
| Small Dial Calibration Linearity over full range | 1 part in 1000 | 1 part in 1000 | 1 part in 1000 | 1 part in 1000 |
| Small Dial Reading Accuracy | 0.1 of Small Dial Division | 0.1 of Small Dial Division | 0.1 of Small Dial Division | 0.1 of Small Dial Division |
| External Temperature Control | Temp. Stabilizer requires 1.00 watts power for a 100° F. differential. Four Rechargeable "D" Size Batteries maintain 90° F. differential for 10 hours and are mounted in removable pack on side of meter. Any 4.5 to 12 volt DC source may be substituted. | None | None | None |
| Small Dial Mechanism | Self counting, read from top and directly coupled (no gears for backlash) with screw which contacts quartz measuring spring. | | Side and top reading, directly coupled (no gears for backlash) with screw which contacts quartz measuring spring. | |
| Large Dial Range — Specify range desired* | 800 Dial Divisions x Large Dial Constant | | | Geodetics not available |
| Large Dial Constant | Standard 6.5 to 12.0 mgls./D.D. | | | Geodetics not available |
| Large Dial Calibration over full range (8 turns) | Curve furnished with values accurate to one part in 1000—measured over full range (8 turns). | | | Geodetics not available |
| Size, Inches: Diameter Height | 7" 14" | 7" 14" | 5½" 10½" | 5½" 10½" |
| Weight, Pounds: Net Including carrying case | 9¾ lbs. 18 lbs. | 7½ lbs. 15¾ lbs. | 5⅛ lbs. 12 lbs. | 5⅛ lbs. 12 lbs. |
| *Price of meter is determined mostly by the Ranges and Dial Constant Specified. | | | | |

***Write for Bulletin No. GM-206***

***WORDEN* Gravity Meters Are Made Exclusively By**

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- **Photographic paper and film are specially packaged to geophysical requirements, and guaranteed fresh.**
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*(Continued from page 38)*

"This margin of power increases the versatility of the E 4 in two ways," said Richard L. Peck, chief test pilot for the aircraft builder. "First, it can do the heavy duty hauling and lifting the 12 E's noted for. But secondly, this extra power is a big margin of safety for executive and other high priority passenger transport."

The E 4 is sold and serviced by aircraft dealers and distributors across the United States and will soon be operated on charter contracts by Hiller helicopter operators throughout the world. For information on dealers or chartered helicopter services, write **Commercial Division, Hiller Aircraft Corp., Palo Alto, Calif.**

## UHF FILTER

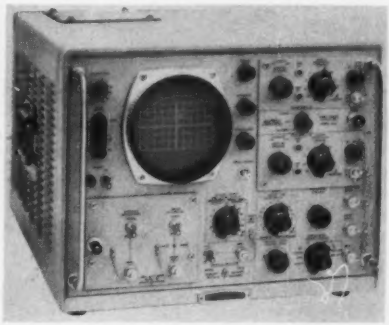
The Special Products Department of **Melpar, Inc.,** a subsidiary of Westinghouse Air Brake Company, recently announced the introduction of a new line of bandpass filters. These unique filters are expected to find wide acceptance throughout the Electronics Industry as a solution to troublesome filter problems at ultra high frequencies.

Using conventional and printed circuit techniques, these filters are available in the frequency range from 200 to 1500 megacycles. Occupying less than 13 cubic inches and weighing only 4 ounces, multistage filters having either maximally flat or Tchebycheff response characteristics provide signal rejection up to 35 db at one bandwidth from the filter center frequency. Bandwidths range from less than 5% to greater than 20%. Maximum passband insertion loss is held to less than 1 db. These filters are designed to meet the environmental requirements of MIL-E-5400 and the vibration requirements of MIL-E-5422.

## WVTR RECEIVER

**Specific Products, 21051 Costanso St., Woodland Hills, Calif.** Model WVTR is battery operated and requires only 3½ in. rack space. Instantaneous carrier frequency selectivity of 2.5, 5, 10, 15, 20 and 25 Mc is crystal controlled. Double conversion, 1990 Kc first i-f crystal converter to 90 Kc second i-f. Sensitivity is 2 micro-Volt, selectivity is 10 Kc at 20 db down. Hi-lo impedance antenna inputs, "S" meter, and phone jack and speaker are provided. Battery or a-c power pack available. Price is $725.

## 15 MC OSCILLOSCOPE



A highly versatile, 15 MC oscilloscope built to exacting military specifications is now available from Hewlett-Packard Company.

The new oscilloscope, Model 160B, is a rugged, dependable instrument meeting requirements of MIL-E-16400B for shock, vibration, humidity and temperature. Premium components are used throughout the instrument, and its high stability tube-transistor circuits assure long life and reliability.

Model 160B's versatility is enhanced by a series of newly-designed time axis plug-in units. These include the Model 166C Display Scanner, which provides the scope with an X-Y recorder output. This output utilizes the full scope bandwidth capability and makes possible large, high resolution, permanent X-Y records of repetitive waveforms. The Model 166D Sweep Delay Generator, another time axis plug-in, provides the standard sweep delay functions and in addition has a unique mixed sweep function which allows observation of low speed and high speed phenomena on the same trace.

New vertical amplifiers plug-ins include the Model 162A Dual Trace Amplifier (20 mv/cm sensitivity), permitting simultaneous viewing of two phenomena or differential amplification of signals dc to 14 MC.

The Model 160B scope provides 24 calibrated sweep times, 0.1 microsecond/

*(Continued on page 69)*

# SEISMOGRAPH SURVEYS*

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# A Message to the Industry on Sub-Miniature Geophones

For some time the trend in seismic instrumentation has moved steadily toward the development of smaller, lighter, more portable equipment.

Inaccessibility of terrain, higher labor costs and ever-increasing competition among seismic contractors have brought about a strenuous effort by instrument makers for new ways to decrease weight and price without loss of performance.

In the geophone field, Hall-Sears has devoted intensive research to this problem. To this research and development program we have brought a background of experience extending back more than a quarter of a century, and a design group that has been outstandingly successful in originating some of the best known geophones now in use.

The result of these efforts is the new HS-J sub-miniature geophone. I sincerely believe this instrument represents our finest achievement and brings to the seismic industry a definite breakthrough in field operations. It opens the way to new techniques and new economies never before possible with heavier equipment.

The response to the announcement of this revolutionary new sub-miniature geophone has been tremendous. The obvious advantages of such a geophone have resulted in a flood of requests for detailed information and test units.

We are indeed gratified at the interest shown in the new HS-J, which is now in full scale production, and take this means to clarify some of the questions most frequently asked.

W. G. Sears

## What is the size of the HS-J?

The HS-J basic unit is 1.1" high by .875 in diameter, and weighs 2 ounces.

## What are its specifications?

The HS-J is available in frequencies from 14 to 30 cps. (Other frequencies are available on order.) Standard impedance is 215 ohms.

## What about performance?

The HS-J, in spite of its small size, has a usable output equal to that of larger single coil types with many times its weight. It is free from spurious resonances.

## Can a geophone of its small size be made rugged enough for severe field usage?

The HS-J incorporates the same fine workmanship for which the HS-1 is famous. It is subjected to the most rigorous testing at 14 stages in the manufacturing operation. Destruction tests consistently show a durability far in excess of that required even in severe field practices with mechanical handling equipment.

## What about initial cost?

Because the HS-J is remarkably low in cost, it has been mistakenly thought by some to be a low performance "competition" model. This is not the case. The low cost of the HS-J has been achieved through modern quantity production techniques without sacrifice of performance or quality materials.

## How about overall economy?

The development of the HS-J has made possible economy of field operations never before possible. Because of its light weight and lighter cabling, crew man-hours are materially reduced. Closer spacing is feasible. Mechanical handling equipment is practical.

Exploration companies are finding it desirable to reappraise their field techniques. Their competitive position dictates the use of the HS-J on many contracts regardless of present equipment inventories.

We believe that the HS-J fills a definite need in a considerable area of exploration work, and that its potential will continue to increase with experience. We invite you to subject this geophone to tests in your own laboratories and in the field.

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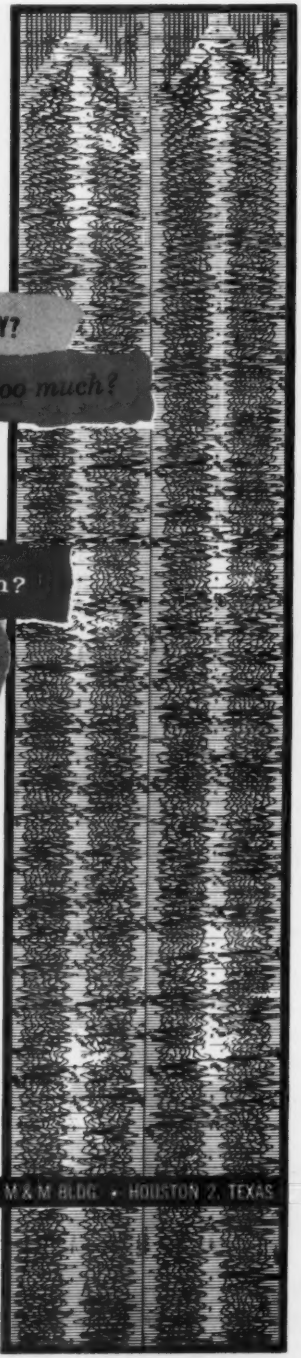

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*Specifically, the 12E's typical payload was a two man survey team, all their equipment, and a 150 lb. drill, plus explosives. Multiply that by the entire 20 man team and you see why the head geologist and party chief called it..."the best helicopter buy in Alaska this summer."*

*In the arctic or the tropics, timberline or shoreline, the 12E's performance will pay off on important jobs in your operations–exploration, offshore taxi and supply, pipeline construction and many more.*

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# MAGNETOMETER
## MAKES 9-MILE SURVEY IN ONE AFTERNOON

Speed is typical of Varian's M-49 portable ground magnetometer. Unlike earlier magnetometers, this revolutionary proton-free-precession instrument measures total field intensity. Hence it requires no leveling, critical orientation or calibration and reads directly in gammas with consistent and accurate repeatability. Freedom from leveling lessens operator fatigue and also provides versatility of use.

This particular survey, done near Mount Diablo State Park in California, included 120 stations. The distance was covered by motor vehicle, but all readings were taken far enough away from the vehicle to eliminate possible error. The survey clearly indicated faults and subsurface geologic features.

The Varian M-49 weighs only 16 pounds. Two miles of traverse per hour can be covered by a man on foot taking readings as often as every twenty paces.

For full information, write the
Varian Instrument Division

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*The Allison 201 Continuously Variable Filter*

**HERE'S A NEW PASSIVE NETWORK FILTER IN THE SUB-AUDIO RANGE**

The new Allison 201 Filter goes into the sub-audio range, yet retains the desirable characteristics of Allison Filters in the audio range. The low noise, low distortion and excellent transient handling capabilities of the 201 make it excellent for heart studies, geophysical work, low frequency vibrations, servo-systems and similar sub-audio frequency spectrum studies.

**ALLISON 201 SPECIFICATIONS**

- Impedance—600 ohms
- Passive network
- 30 db per octave attenuation rate
- Independent high cutoff and low cutoff sections
- Low insertion loss
- Smooth pass band
- Negligible ringing
- Frequency coverage—1 to 256 cps
- Shipping weight: 35 lbs.
- Price: $695.00 FOB Factory

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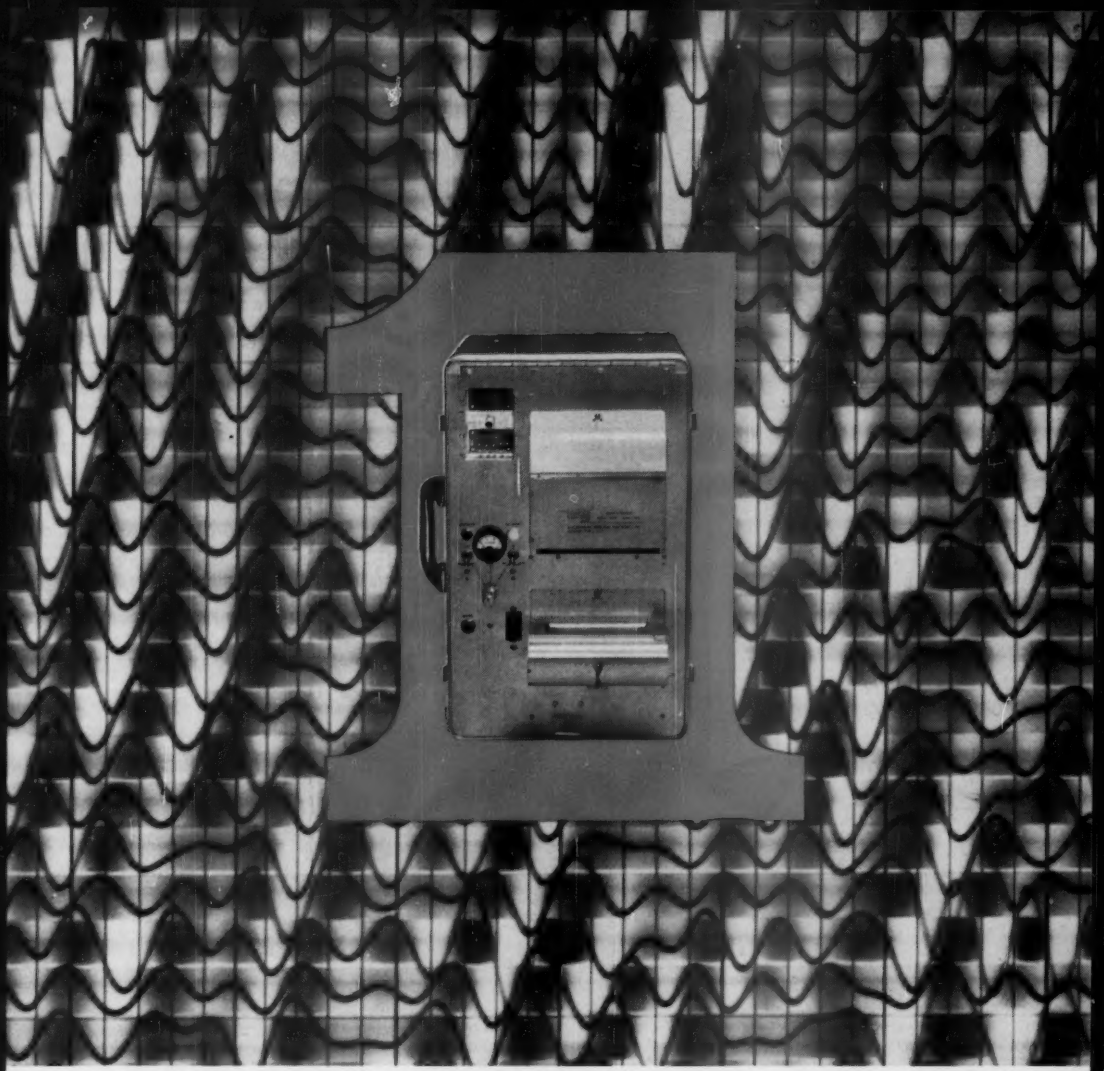

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From SIE comes the first triple-recording oscillograph requiring only one galvo block. ■ Choose variable-density, variable-area, conventional wiggle or variable-density-and-wiggle combined. Simple lens-box change converts from variable-density to variable area. ■ Timing lines may be generated internally from either flasher tubes or standard timing motor. Consistency of paper drive is assured by a synchronous motor with built-in 400 cps power supply. ■ Answer all your oscillograph recording needs with one instrument, the TRO-6.

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...including a new transient storage system which produces automatically a Fourier series plot of a single pulse or wavelet ...now available through our associated company, Technical Products Co., Instrument Division. Write or call Techno for complete information and literature.

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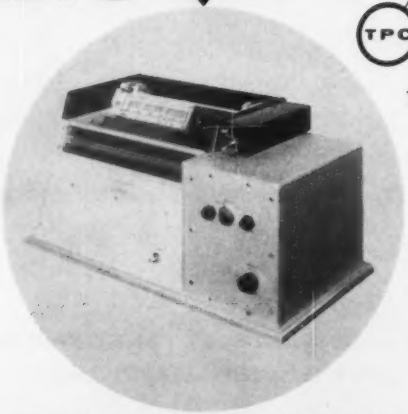

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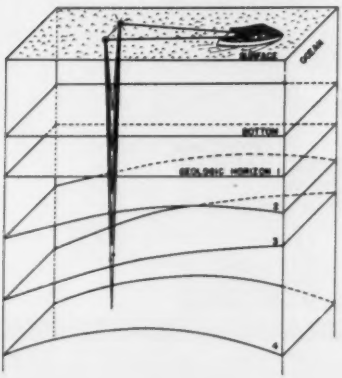


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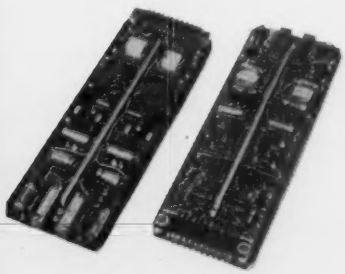

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In addition to the latest advancement in portability, the new "RecorData" (PMR-20) gives you:

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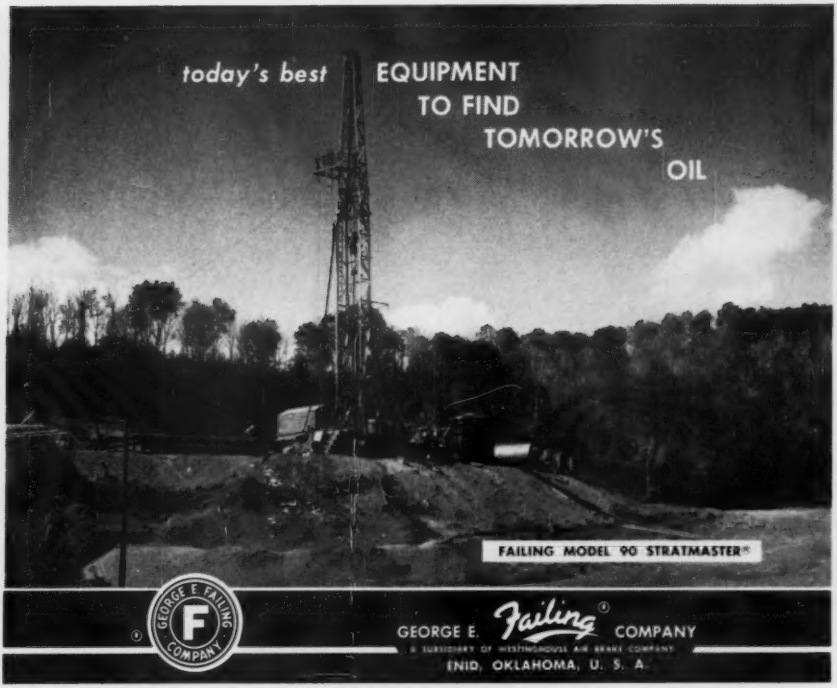


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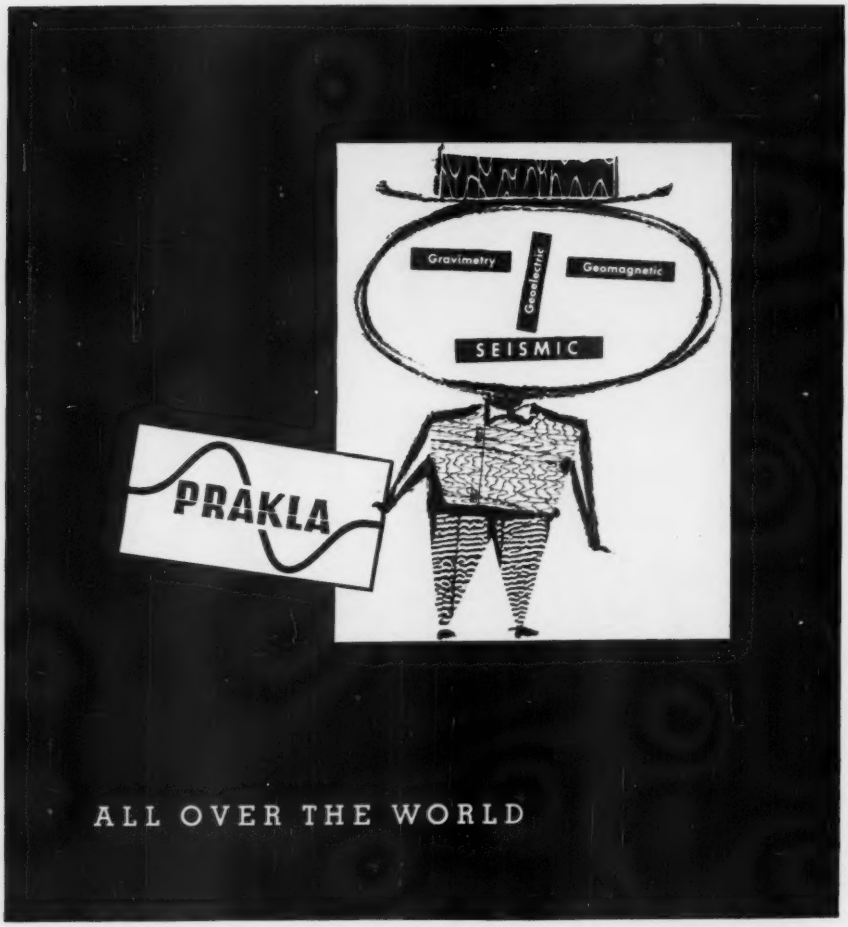


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# WHEN ACCURACY IS A MUST World-Wide Gravity Meters Are Your Best Buy . . .

Exploration crews the world over are using more World-Wide Gravity Meters than ever before — for good reasons! Weighing only eight pounds, this economical, *built-to-take-it*, portable meter operates anywhere in the world in all kinds of weather with maximum accuracy. World-Wide's easy-to-read meter is thoroughly temperature compensated, requires *no thermostats, no barometric temperature corrections.* Sealed in a vacuum, the World-Wide Gravity Meter gives dependable, trouble-free service in the most difficult prospect areas.

*Exclusive Features Of The World-Wide Gravity Meter:*

- Easy reading counter . . . operator reads the meter without removing from the tripod.
- Recessed level bubble . . . eliminates level bubble creep.
- World-wide range on all meters . . . regardless of latitude.
- Approximately 100 milligal range on counter . . . minimizes resetting instrument in rugged terrain.

World-Wide Gravity Meters are available on purchase or rental/purchase plans. Each instrument carries a full-two-year warranty. Write or wire for complete details.

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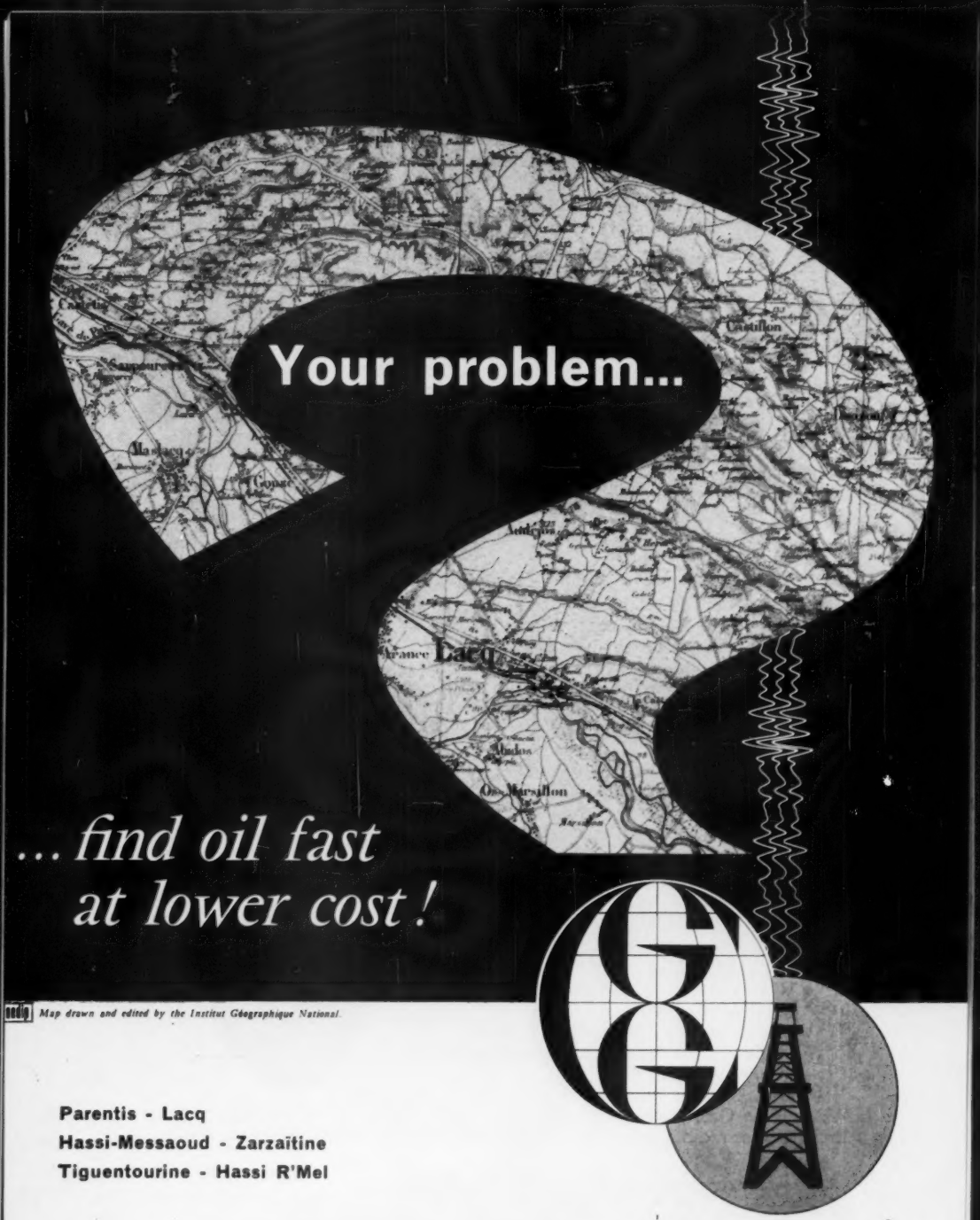
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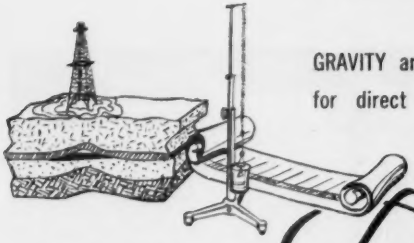

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*(Continued from page 50)*

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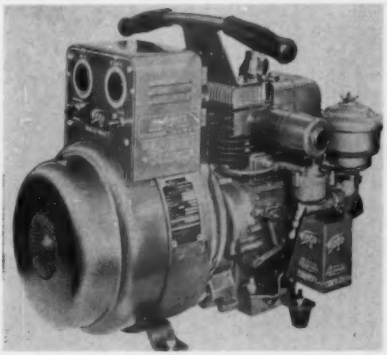

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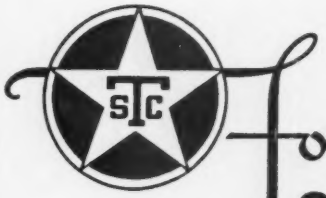


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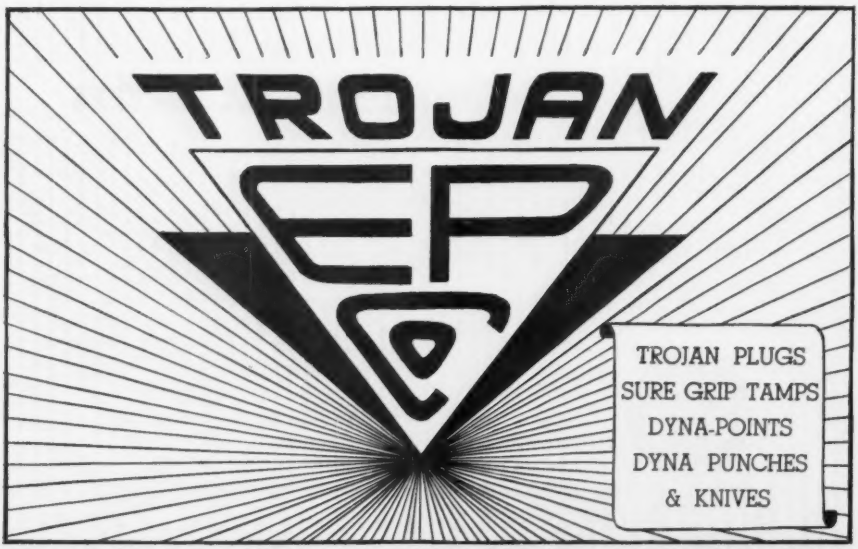


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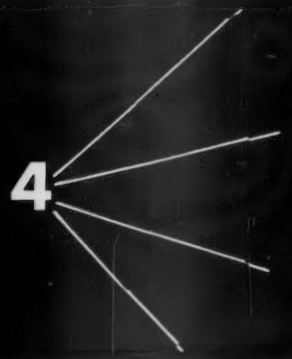


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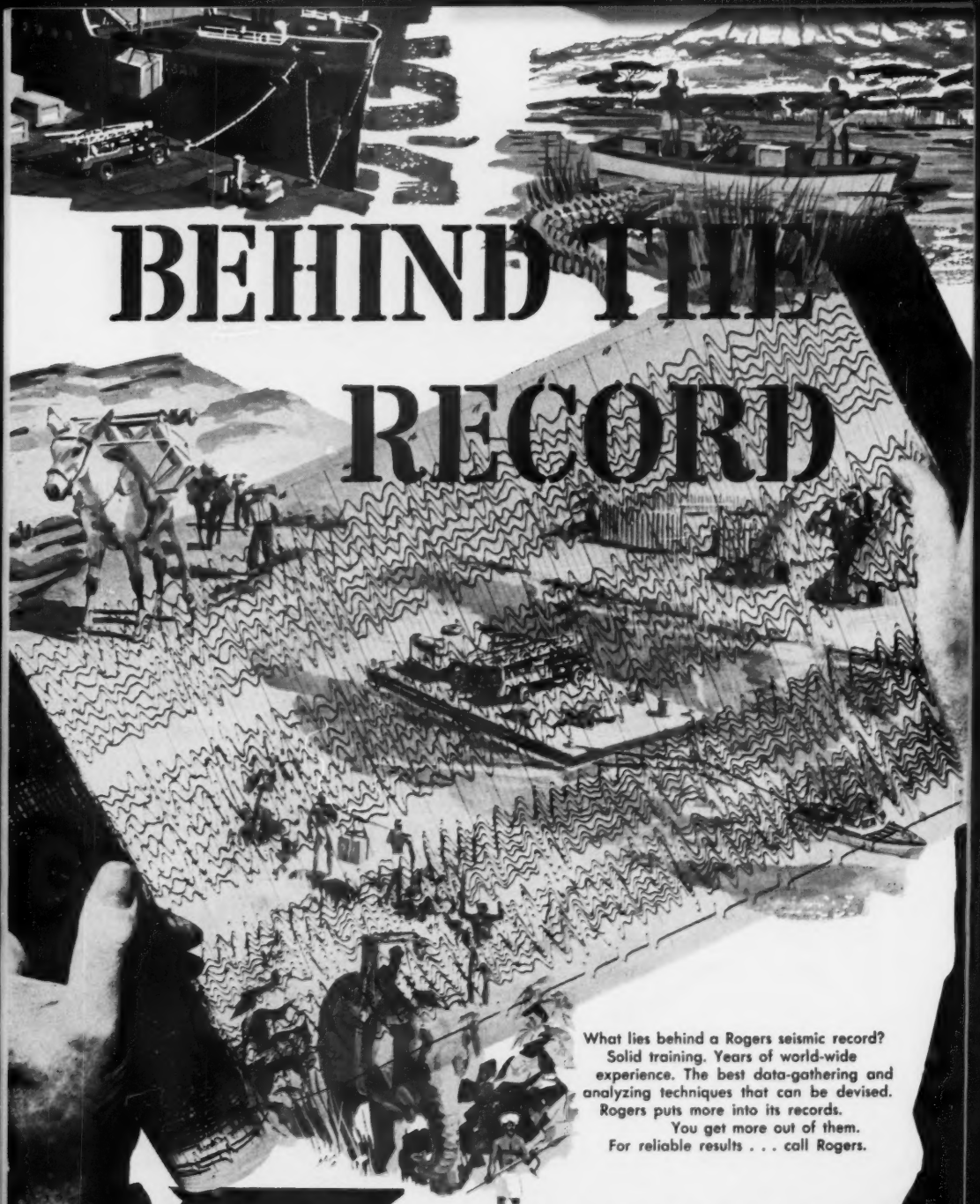


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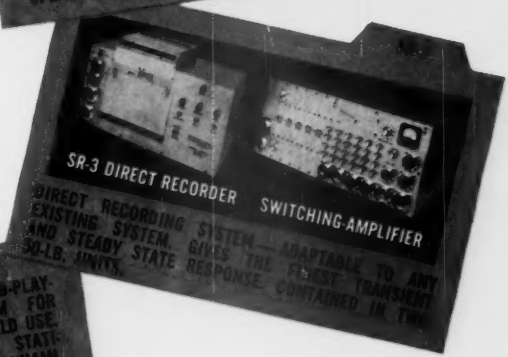

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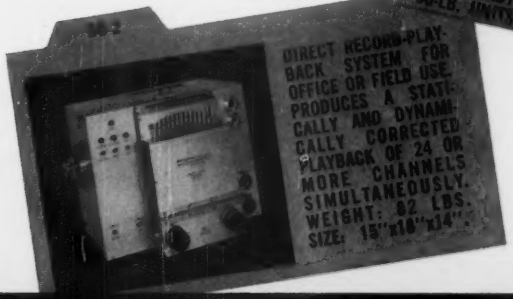

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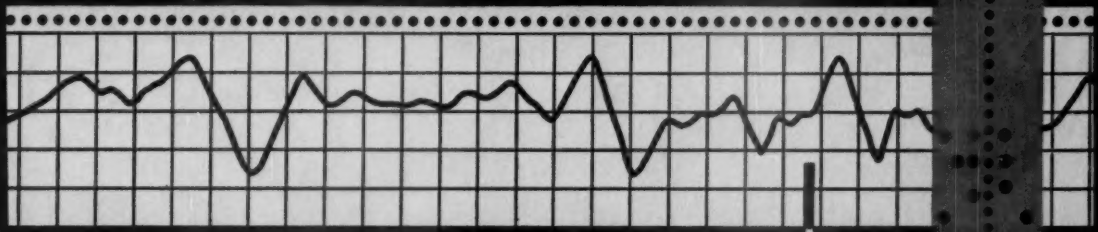

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